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EIGHTH QUARTERLY PROGRESS REPORT (COVERING JANUARY THROUGH MARCH 1978)

on

ACCELERATED/ABBREVIATED TEST METHODS, STUDY 4 OF TASK 3 (ENCAPSULATION) OF THE LOW-COST SILICON SOLAR ARRAY PROJECT

JPL CONTRACT NO. 954458

The JPL Low-Cost Silicon Solar Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DoE.

Prepared April 3, 1978

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF TABLES

LIST OF TABLES (Cont'd)

I. SUMMARY

To meet the goals of the LSSA program, solar cell encapsulants must provide protection for 20 years. Consequently, the objective of the present program is to develop methodology for making confident predictions of encapsulant performance at any exposure site in the U.S.A.

During the first year of the program, inherent weatherability was studied. Inherent weatherability is controlled by the three weather factors common to all exposure sites: insolation, temperature, and humidity. Emphasis was focused on the transparent encapsulant portion of miniature solar cell arrays by eliminating weathering effects on the substrate and circuitry (which are also parts of the encapsulant system). The most extensive data were for yellowing, which was measured conviently and precisely. Considerable data also were obtained on tensile strength. Changes in these two properties after outdoor exposure were predicted very well from accelerated exposure data. This is remarkable considering that outdoor UV intensity data is very limited. In addition, the feasibility of predicting an important but difficultly-measured property by correlation with an easily-measured property was demonstrated. Although more outdoor exposure data will be received, mathematical modeling studies are continuing. This first part of the program can be said to be successfully concluded.

In continuation of the inherent weatherability study, the power output of solar cells was monitored under accelerated test conditions and is being followed for outdoor exposures. For this purpose, Universal Test Specimens (UTS's) with nine different substrate/transparent encapsulant combinations were prepared. Again, the objective is to predict outdoor performance from accelerated exposure data with photochemical stresses of about 8 times normal. Continuous accelerated exposure under 8 key combinations of ultraviolet (UV) light intensity, temperature, and humidity was continued for 2 months. Then the same UTS's were exposed to 100 percent relative humidity at 100° C for one month. Degradation effects are discussed and illustrated in this report.

A subsequent objective is to accelerate degradation rates by a factor of 100 or more. This includes the purely thermal reactions, such as hydrolysis, as well as the photochemical reactions. The photochemical acceleration is the more difficult problem. Use of natural sunlight avoids the problem of imperfect matching of the solar spectrum by lamps. Therefore, plastic films which had been studied previously were exposed to up to 1400 suns at the Army's solar furnace at White Sands, New Mexico. The amount of acceleration was as expected. Data are being analyzed.

II. INTRODUCTION

The first year study (inherent weatherability of transparent encapsulants) is essentially complete. Successful predictions for the rate of loss of properties on outdoor exposure were made for plastic films based upon accelerated data. These predictions were summarized in the Sixth Quarterly Progress Report and will be presented in a paper at the Conference on Aerospace Transparent Materials and Enclosures, Long Beach, CA, in April of this year. Degradation data for samples exposed beginning in winter and summer are still being monitored. The electrical performance of solar cells in UTS's exposed outdoors is also being followed.

The second year study involves UTS's with several transparent encapsulant-substrate systems which are relatively rapidly degraded on outdoor exposure. The key property being followed is maximum power output of the solar cells. Results of the accelerated exposure program are discussed below. Outdoor samples will continue to be returned at intervals and tested.

Of special interest is the possibility of hyperacceleration of photochemical degradation, e.g., by 100 times. Feasibility was shown by exposing samples to mirror-concentrated sunlight in a solar furnace. Data are discussed below.

III. DISCUSSION OF RESULTS THIS QUARTER

A. First Year Study (Inherent Weatherability of Transparent Encapsulants)

1. Transparent Plastic Films

a. Master Plot of Seasonal Outdoor Absorbance Data for Lexan

Results, except recent data on outdoor samples, have already been tabulated (Reference 1). Predictions were summarized in the Sixth Quarterly Progress Report (for July through September 1977).

Using early seasonal degradation rate data to estimate "exposure factors," the increase in absorbance at 360 nanometers for Lexan exposed in Phoenix or Miami could be plotted into one approximate line regardless of the time of year when exposure started (Figures 1 and 2). The method was as follows.

First, an exponential model was assumed. This at least approximately fits the facts, and its use simplifies calculations. Also, this model corresponds to a simple photochemical reaction in which the accumulated chromophore (colored species), which is directly proportional to absorbance, is also directly proportional to the total UV energy (in the appropriate wavelength region) received.

Next, early seasonal absorbance data were used to estimate "monthly rate factors" (Table I). These factors were plotted vs. month of the year, and a smooth curve was drawn through the points for each of the two sites. NOTE: These data imply Phoenix has more UV variation than Miami (at about 300 nm, the wavelength region causing yellowing of Lexan).

Finally, the "exposure factor" for a given sample was calculated by averaging the "monthly rate factors" for the months of exposure and multiplying by the number of days of exposure. For example, the sample exposed in Phoenix for 300 days starting on 12/22 was outdoors during January ("monthly rate factor" = 1.0), February (2.0), March (2.7), and so on through October (1.8). The average of the "monthly rate factors" is (1.0 + 2.0 + 2.7 + ... 1.8)/10 = 2.7, and 2.7 x 300 = 810. $\mathrm{Log}_{10}(810) = 2.91$, at which time $\log_{10}(\frac{1}{P}) = 0.6958$, and this point will be found plotted in Figure 1.

Convergence of data points (Figures 1 and 2) by this method is far closer than had been attained using "exposure factors" assumed from UV data in the literature. Although an exponential model (Weibull plot with slope = 1) had been assumed in handling the seasonal effects, the later data points fall into a line with slope = about 2. That is, the model is the Weibull model: $P = e^{-\lambda(UV)^2}$. This means that the chromophore concentration is proportional to the square of UV light deposited on the sample. However, other models, such as the lognormal, remain to be tried and may also fit.

A rationalization for the increase in absorbance being proportional to the square of UV light deposited is that as the chromophore concentration increases more of the degrading UV light is absorbed so that the reaction is "autocatalytic".

b. Example of Empirical Curve-Fitting Using Lexan Accelerated Exposure Data

An example of empirical curve-fitting is shown in Figure 3. The following equation was selected from Reference 2:

$$y = ae^{b/x}, \text{ where b is less than 0.}$$

linear form: $\ln y = \ln a + b/x$

The quantity $\log_{10}\left[1000 \log_{10}(\frac{1}{P})\right]$ was defined as y, and ln (time, hours) was defined as x. A suitable value of "a" was found by trial and error to be 3.55. Then, using the value of $\log_{10}(\frac{1}{P})$ found for 24 hours, "b" was calculated to be -1.21. Thus, the linear form of the equation became:

$$\ln\left\{\log_{10}\left[1000 \log_{10}(\tfrac{1}{P})\right]\right\} = 1.27 - 1.21/\ln t,$$

where t = time in hours and P = fraction of original transmittance at 360 nm.

The factor of 1000 was used for convenience and subsequently removed. Figure 3 shows that a good fit was achieved. This is a Weibull plot. If $\ln\left\{\log_{10}\left[1000 \log_{10}(\frac{1}{P})\right]\right\}$ were plotted on the ordinate and 1/ln t on with abscissa, a straight line would result, with slope -1.21.

2. Universal Test Specimens (UTS's)

Electrical data are now complete for UTS's exposed for 420 days in Phoenix and in Miami. Results are given in Table II. The average percent of original power retained for the 6 solar cells in each UTS was 100 for Phoenix, 82 for Miami, 93 for the EMMA, and 99 for the EMMAQUA. The degraded power output in Miami may be due to moisture-induced corrosion of cell metallization caused by high humidity. The field effect transistors (FET's) still have shown no notable increase in leakage current. (However, FET's do operated as expected. For example, accelerated exposure of the "second generation" UTS's followed by steam exposure increased leakage currents up to 10^5 times. Outdoor exposure of the new UTS's also caused high leakage currents in some cases.)

In physical appearance, the exposed Sylgard 184 encapsulant was dulled and slightly dusty on the surface in all cases. On the other hand, it was quite clear internally. The Tedlar remained glossy and

and colorless in all cases. The Lexan became yellow on exposure but maintained its integrity after the 45°S exposures. Note that unsupported Lexan samples were brittle and retained only about 25 percent of original tensile strength after 300 days in Phoenix or Miami. Such a low tensile strength normally means loss of integrity. However, Lexan cemented to the Sylgard 184 on UTS's was still intact after 420 days. This is an example of favorable interaction of encapsulant components. After EMMA exposure, the Lexan was deep yellow, rough-surfaced, and showed one large crack. During EMMAQUA exposure, the Lexan cover was almost completely lost. However, there was no visible effect of exposure on the ceramic substrate or gold-plated circuitry. Assuming an acceleration factor of 6, 420 days of EMMA(QUA) exposure represents 7 years of normal exposure.

Four UTS's are still on exposure for each of the four conditions. The next samples will be returned at 540 days.

B. Second Year Study

1. Inherent Weatherability of UTS's with Nine Different Encapsulant-Substrate Combinations

a. Outdoor Exposure

The nine array systems are described in our Sixth Quarterly Progress Report. Outdoor exposure began at Miami (45°S) on 10/31/77 and at Phoenix (45°S, EMMA, EMMAQUA) on 10/23/77.

Samples have been returned after 30, 60, and 90 days of exposure. As expected, there was no significant reduction in solar cell power after 30 days. FET leakage current became high in a few cases. The other samples are being electrically tested. Visible changes in transparent encapsulants and copper circuitry were generally slight through 90 days. The next sampling point is 180 days.

b. Accelerated Exposure

i. Data Obtained

Accelerated (xenon lamp) exposure of twenty-four UTS's (eight with each of the three substrates: ceramic, enameled steel, and epoxy) was ended after 61 days. Results are summarized in Tables III - V and Figures 4 - 15.

These UTS's were next exposed to steam at 100^{o} C for 12 days. Considerable additional degradation occurred. Results are summarized in Tables VI - XI and Figure 16.

Finally, the same UTS's were exposed again to steam for an additional 19 days, bringing the total time of steam exposure to 31 days. Results are summarized in Tables XII - XVIII and Figures 17 - 26.

Note that the in situ solar cell power data are approximate. The Figures (4 - 15, 17 - 26) illustrate scatter in values during "plateaus" of performance vs. time.

ii. Observations

Figure 13 shows nitrocellulose lacquer after exposure to all 8 accelerated conditions. It illustrates the advantages of multicondition exposure in clarifying the relative effect of UV light, temperature, and moisture. For convenience, the nine photographs will be referred to as #1, 2, and 3 from left to right across the top, #4, 5, and 6 across the middle, and #7, 8, and 9 across the bottom. The following conclusions are drawn by comparing these photographs. Figures 15, 16, and 26 also are referred to.

(1) The most pronounced visible degradation (blistering) is caused by:

(a) More UV - #6 worse than #9
#5 worse than #8

(b) Higher temperatures - #6 worse than #4

(c) Increased humidity - #6 worse than #5
#4 worse than #3
#7 worse than #2
#9 worse than #8

(2) Blistering is proportional to light intensity. Compare #9 with #7, showing a relatively fine "orange peel" texture, and with #6.

(3) Photograph #3 represents NOCT at noon in a dry, desert climate. Photograph #4 represents NOCT at noon in a moist climate such as Miami. These results illustrate the dramatic differences in encapsulant performance possible for dry vs. wet sites.

(4) Incidentally, referring to Figure 15, the effect of humidity in causing loss of gloss of the polyurethane encapsulant is clearly shown.

(5) The nitrocellulose lacquer was degraded by moisture alone, with no previous UV exposure, at 100° C (Figures 16 (right column) and 26). However, previous UV exposure without moisture caused greater degradation in subsequent steam exposure. Therefore, weather factors can have a sequential effect.

(6) Under prolonged exposure, an encapsulant can become <u>less</u> opaque. For example, see Figures 16, 23, and 26 for nitrocellulose lacquer originally exposed at 0 rel. UV, 72° C, and 100 percent R.H. There remained less material after 31 days of steam exposure than after 12 days. Consequently, the solar cell power <u>dropped</u> to about 50 percent of original at 12 days steam exposure and <u>rose</u> to about 95 percent at 31 days. The same effect is seen for nitrocellulose lacquer originally exposed to 0.66 rel. UV, 64° C, and 100 percent R.H. (Figures 16, 23, and 26) and also for acrylic lacquer originally exposed to 0.66 rel. UV, 64° C, and 100 percent R.H. (Figures 16, 20, and 26).

Other observations are:

(1) Power loss by the solar cells was surprisingly little as encapsulants darkened and/or became opaque. For example, the loss was as little as 10 percent despite darkening of polyurethane encapsulant to the point of visual opacity. Opaque (milky) acrylic lacquer caused as little as 15 percent power loss. See Figures 16 and 26 for other examples.

(2) With no encapsulant, solar cell metallization (Ti/Ag coated with solder) resisted 100 percent relative humidity at 72° C for 61 days followed by steam at 100° C for 31 days.

(3) There was no obvious effect of encapsulant degradation products on the cells.

(4) Field effect transistors (FET's) gave leakage currents up to 10^5 times the original value after steam exposure.

(5) Enameled steel is a promising substrate.

(6) Two promising encapsulants are acrylic lacquer and a rubbery polyurethane pottant with glass cover.

(7) Copper circuitry may be feasible for modules if properly protected.

(8) The feasibility of taking in situ power readings during multicondition exposure was demonstrated (Figures 4 - 12 and 17 - 25). Tape cables for this purpose were soldered to the edge contacts of the UTS's. Continuation of such measurements for a year, assuming a conservative time-compression "acceleration factor" of 8, would give performance vs. time curves simulating 8 years of outdoor exposure.

(9) Disparities in performance between paired solar cells were generally not great in accelerated exposure (Figures 4 - 12) but were sometimes very large in steam exposure (Figures 17 - 25). One reason is that the Cu-plated Mo/Mn circuitry on the ceramic substrate (Figures 17 - 19) often corroded to failure. A longer circuitry path provided more opportunity for corrosion to reduce power, as shown in Tables IX and XV.

(10) The originally high resistance of the Cu-plated Mo/Mn circuitry lines is indicated by the fact that the direct probing of cells attached to short lines gave no higher than 111 percent of original power (Figure 17), while probing cells attached to longer lines gave up to 146 percent of original power (Figure 18).

iii. Predictions

The plan was to follow the moisture-induced degradation of solar cell metallization (Ti/AG) as a measure of protection, essentially by moisture exclusion, afforded by the encapsulants. However, the solder-coated metallization proved to be very moisture-resistant. Survival at 72^{o} C and 100 percent relative humidity for 2 months suggests, by the rule of thumb that reaction rate doubles for each 10^{o} C rise in temperature, a lifetime of at least $2x2^3 = 16$ months under the most humid conditions at an average "kinetic temperature" of 40^{o} C. Further, the following month of survival in steam at 100^{o} C suggests an additional minimum lifetime of $1x2^6 = 64$ months. The total is 16+64 = 80 months, or a minimum lifetime of about 7 years.

Steam exposure was an expedient for the purpose of forcing failure of the unexpectedly moisture-resistant cells. The cell metallization survived, but degradation of the cover encapsulants was interesting, especially in regard to the surprisingly small effect of visual opacity on solar cell power. However, the steam temperature (100° C) may have given unrealistic results. For example, 100° C is considerably over the Tg of the acrylic lacquer, which was found by differential scanning calorimetry (DSC) to be about 63° C, at which temperature stress relief occurred. Therefore, a hydrolysis reaction may have been forced. This presumably resulted in a milkiness improbable under real conditions.

Accelerated exposure data lead to predictions of maximum solar cell power. This should remain at over 90 percent of original for all the array systems under conventional (45°S) exposure for at least 1.5 years, assuming an "acceleration factor" of 9. Similarly, the acrylic lacquer (System #4) and the glass/polyurethane encapsulants (Systems #3, 6, and 9) are predicted to remain unchanged after 1.5 years. The only accelerated conditions that degraded the acrylic lacquer were at a UTS temperature of 72° C, which exceeds the Tg of 63°C as determined by DSC. Similarly, Tedlar was degraded only above its Tg (57° C by DSC) in accelerated exposure (Reference 1). On the other hand, severe degradation of nitrocellulose lacquer (System #7) is predicted at 1.5 years.

2. Hyperacceleration by Highly-Concentrated Natural Sunlight

These tests were conducted at the White Sands Missile Range in February. The plastic films under test were immersed in rapidly flowing water (5 liters/minute) in a quartz vessel (7.8 x 5.2 x 25 cm. ID, 2 mm. wall thickness). The light passed through 5.2 cm. water, which absorbs essentially all energy of wavelength above 1.3 microns (about 17 percent of the solar constant). Calorimetric readings were made on light actually passing through the sample, which was placed against the back inner surface of the vessel. The water entered the vessel at about 14° C and exited at about 35° C. This method worked smoothly, although clouds and gusty winds frequently interrupted operation of the furnace. The water-immersion method is valid because air and water have little effect on the photochemical yellowing reactions (Reference 1).

Absorbance data are given in Tables XIX and XX. The best of these data, obtained at 1400 suns (33 cal./cm.^{2}/sec.), are plotted in Figure 27. Points from accelerated testing are included for comparison. Within experimental error, there appears to be no real difference in the slopes of lines through the experimental data. Rough calculations indicate that the order of magnitude of acceleration is as expected. We hope to obtain UV data to refine these calculations. The 4 hour exposure of Lexan gave about the same degree of yellowing as attained in 280 days of natural exposure (tilted 45°, facing south) near Phoenix starting in September. Similarly, the 4 hour exposure of polystyrene equaled 150 days of exposure in Miami starting in October.

Tensile test results on the films exposed to 33 cal./cm.^{2}/sec. are shown in Tables XX and XXI.

The breaking stress of polystyrene was still about 84 percent of original after 4 hours, at which point $\log_{10}(\frac{1}{P})$, where P = fraction of original transmittance at 360 nm., was 0.26 (Table XX). After 150 days of 45°S exposure in Miami, both results were exactly the same. Tensile data are only approximate, but the point is that hyperaccelerated exposure with natural sunlight matched natural exposure in the correlation of two dissimilar properties. In the xenon lamp exposure, $\log_{10}(\frac{1}{P})$ of about 0.20 was attained at 35° C and 100 percent relative humidity in 120 hours. At this time the tensile strength was 76 percent of original. These data agree roughly with the above.

In the case of Lexan, unlike polystyrene, xenon lamp exposure had over-accelerated the increase in $\log_{10}(\frac{1}{P})$ vs. loss of tensile strength. After 768 hours of xenon lamp exposure at 35° C and 100 percent relative humidity, $\log_{10}(\frac{1}{P})$ was about 1.1 and the tensile strength was 52 percent of original. In contrast, outdoor exposure results for $\log_{10}(\frac{1}{P})$ and percent of original tensile strength were, respectively, 0.48 and 27 (Phoenix, 45°S), 0.46 and 27 (EMMA), and 0.64 and 31 (EMMAQUA). When $\log_{10}(\frac{1}{P})$ reached about 1.1 on the EMMA or EMMAQUA, the tensile strength dropped to about 7 percent of original. Solar furnace exposure gave $\log_{10}(\frac{1}{P})$ = 0.46 and 26 percent of original tensile strength at 4 hours (Table XXI), which agrees well with the outdoor results. These data show that the solar furnace exposure matched natural exposure in the correlation of two dissimilar properties for Lexan as well as for polystyrene.

The conclusion is that hyperaccelerated exposure using natural sunlight is a feasible test method and an important step in predicting 20-year outdoor lifetimes.

The alternative of using exposure data obtained over a short time of less than 2 years lies in the difficulty of extrapolating data. Figures 28 and 29 give a hypothetical example. The four data points, covering up to 5 months, precisely fit a lognormal model (Figure 28) but can easily be construed to fit a Weibull model also (Figure 29). The usual experimental errors permit no distinction and, in fact, could favor the wrong model. At 20 years ($\log_{10}$ (time, days) = 3.86), the lognormal extrapolation gives $\log_{10}(\frac{1}{P})$ = 0.86 or P = 0.14, and the Weibull extrapolation gives $\log_{10}(\frac{1}{P})$ = 1.44 or P = 0.04. Another possibility is that degradation follows neither model but rather the dotted curve in Figure 28. This curve resembles the one for Lexan empirically modeled above. In this case, the xenon lamp's output of short-wavelength UV was continuously decreasing (Figure 3). At 20 years, the dotted curve in Figure 28 gives $\log_{10}(\frac{1}{P}) = 0.45$, or $P = 0.35$.

Consider what the consequences of extrapolation could be. If property P were tensile strength, and if retention of 1/3 the original strength were required for integrity of an encapsulant, then the dotted curve (Figure 28) would represent a 34 year life, the lognormal model (Figure 28) would represent a 6.1 year life, and the Weibull model (Figure 29) would represent a 2.4 year life.

This illustration shows why careful data gathering and judicious mathematical modeling are essential, especially if a hyperaccelerated 20-year value is not available.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. One important conclusion is that photochemical reactions of encapsulants can be accelerated over 100 times without changing chemical mechanisms. Such hyperacceleration is a valid test procedure, i.e., natural degradation pathways are followed. This possibility should be investigated further. For example, even full-scale modules could be subjected to "20 years" of UV light and then exposed at elevated temperature/humidity to accelerate degradation.

2. Early test results suggest that one low-cost solar array includes acrylic lacquer (or glass-covered polyurethane) as the transparent encapsulant, copper (or perhaps aluminum) circuitry, and enameled steel as substrate.

3. Final conclusions and recommendations will be made in the Final Report (draft copy due in hands of JPL on April 30, 1978).

V. PLANS FOR NEXT QUARTER

1. Examine weathered samples by Fourier transform attenuated total reflectance infrared spectroscopy (ATR).

2. Complete measurement of properties of UTS's and films returned to date from the outdoor exposure sites.

3. Prepare draft of Final Report (due April 30, 1978).

VI. REFERENCES

1. Interim Report, this contract, ERDA-JPL-954458-77/2, prepared October 24, 1977.

2. C. Daniel and F. S. Wood, Fitting Equations to Data, Wiley - Interscience, 1971, page 22.

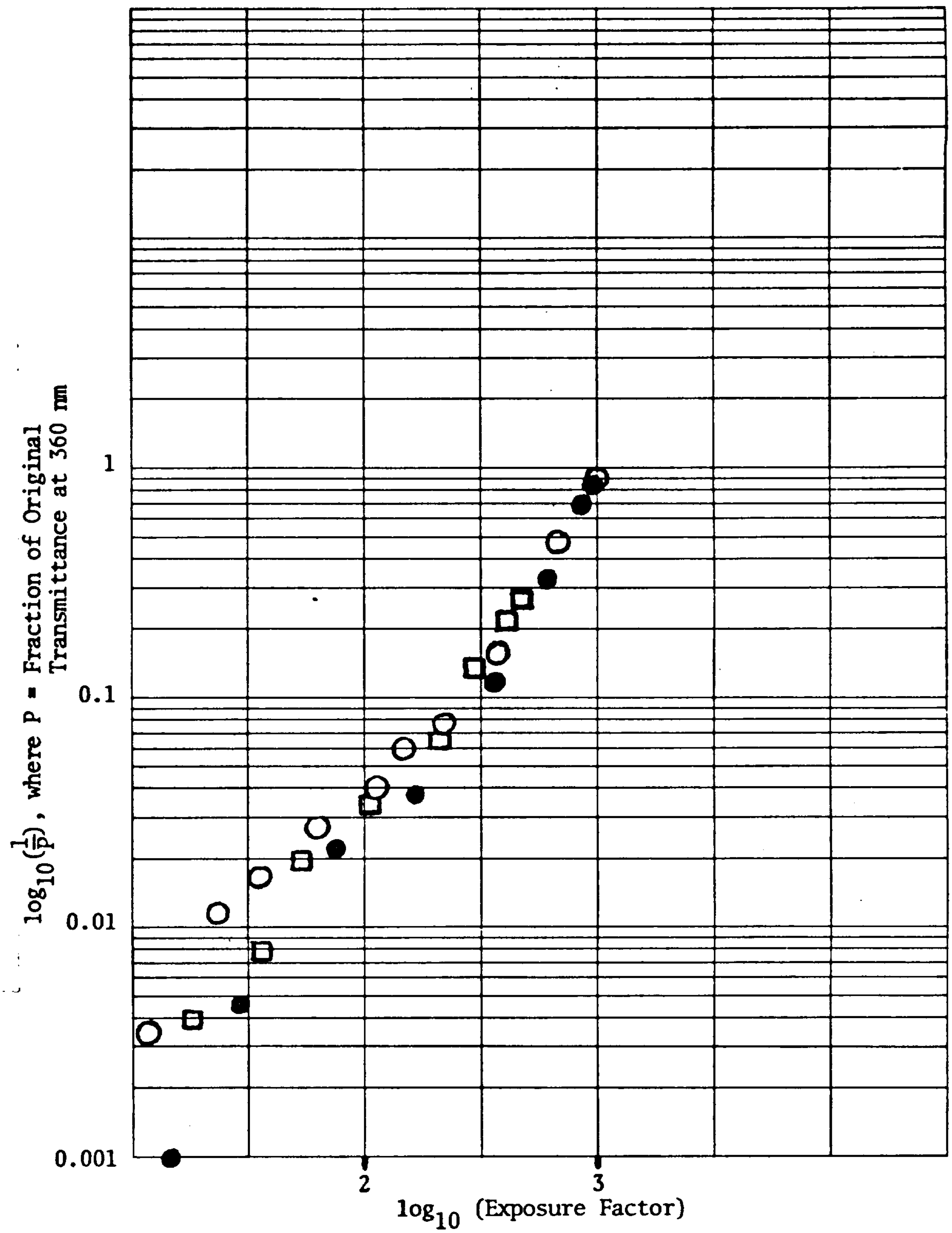


Figure 1. Yellowing of Lexan in Phoenix (45°S)

○ Exposure started 9/12/76
● Exposure started 12/22/76
□ Exposure started 6/21/77

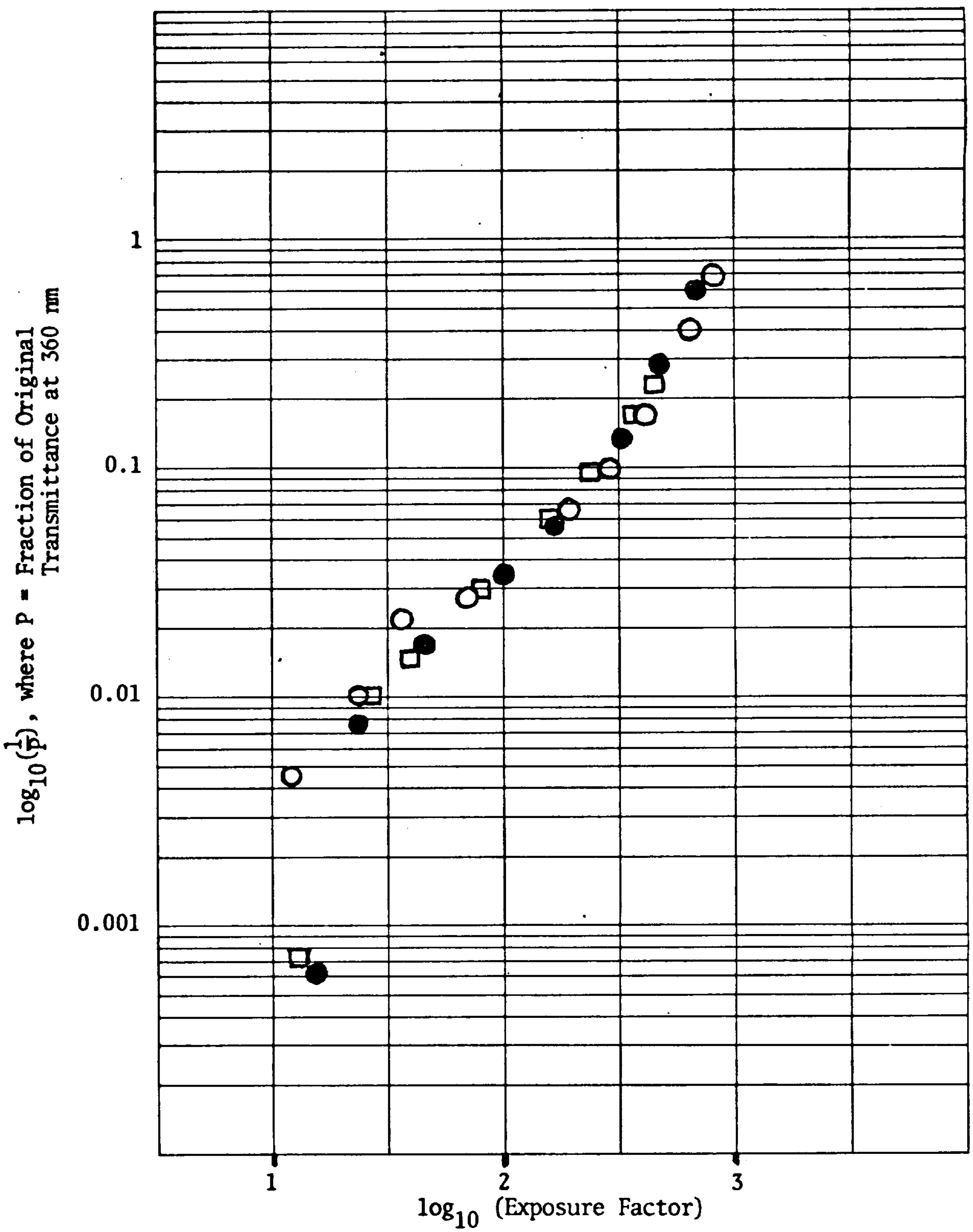


Figure 2. Yellowing of Lexan in Miami (45°S)

○ Exposure Started 9/1/76
● Exposure Started 12/22/76
□ Exposure Started 6/21/77

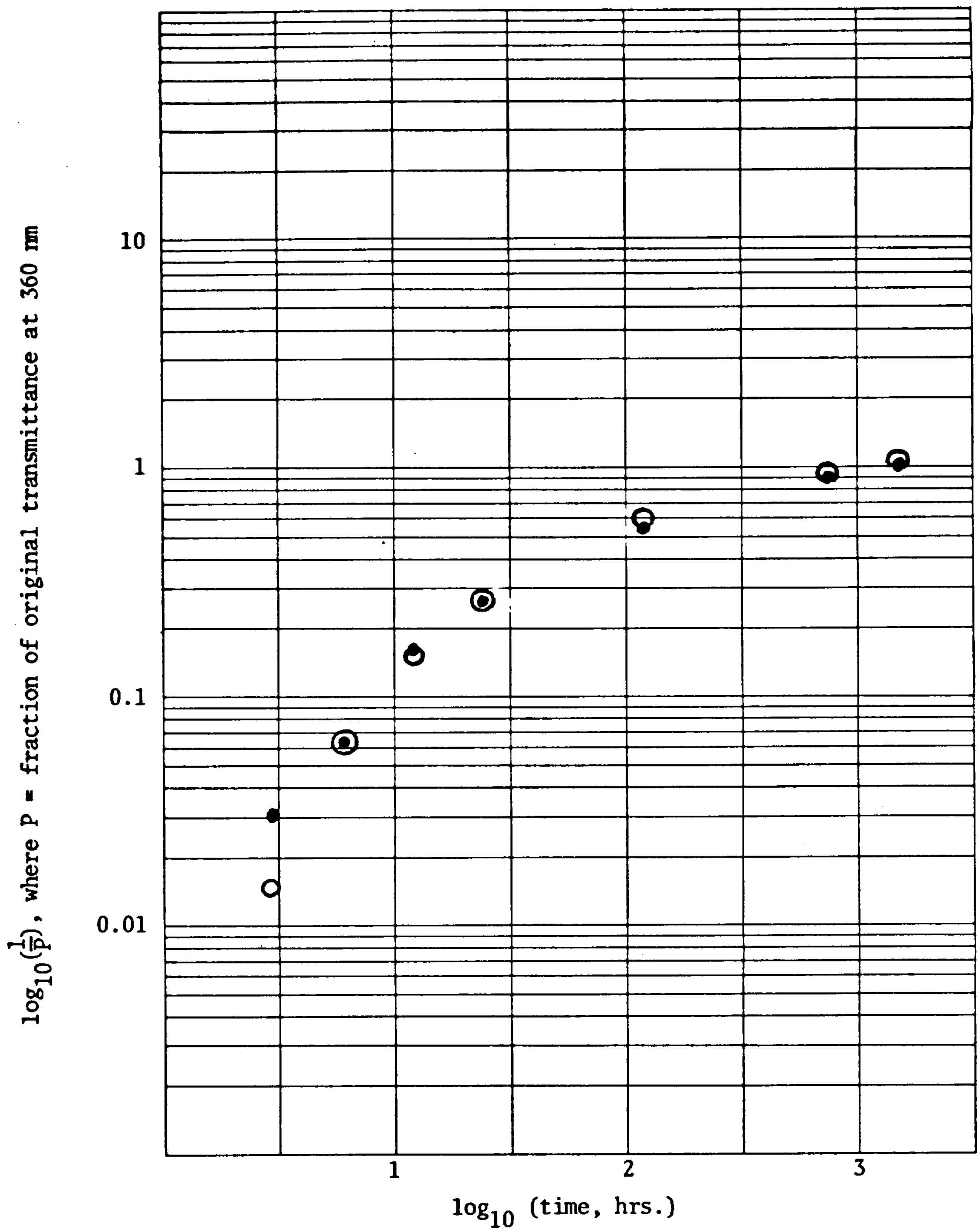
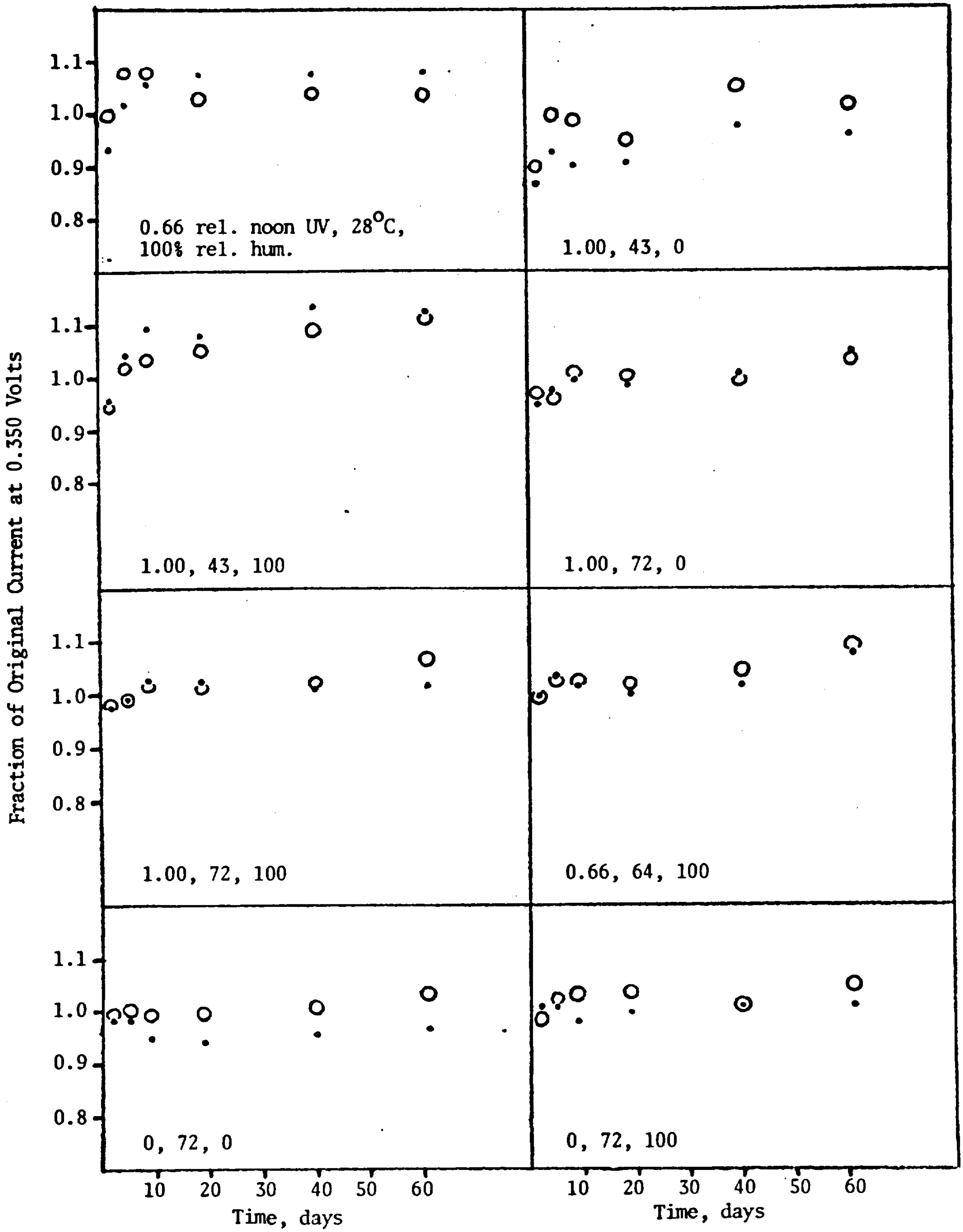


Figure 3. Absorbance Data for Accelerated Exposure of Lexan (1.00 rel. noon UV, 26°C, 0% relative humidity).

● = Found

O = Calculated (see text)

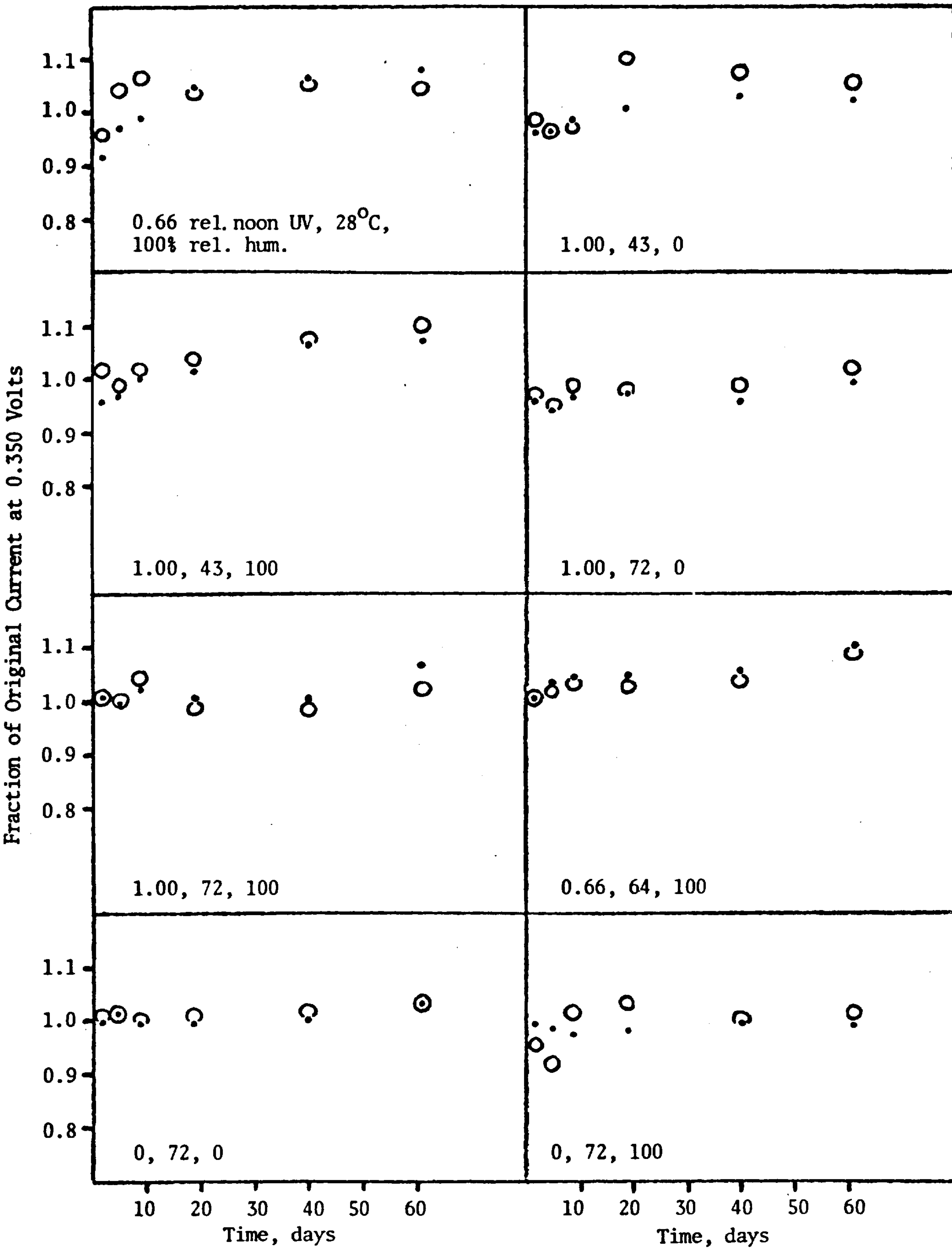
Figure 4. Change in Solar Cell Power During Accelerated Exposure: Array System 1*



*Encapsulant: none, Substrate: ceramic, Circuitry: Mo/Mn + Cu

• = Cell 3, O = Cell 6

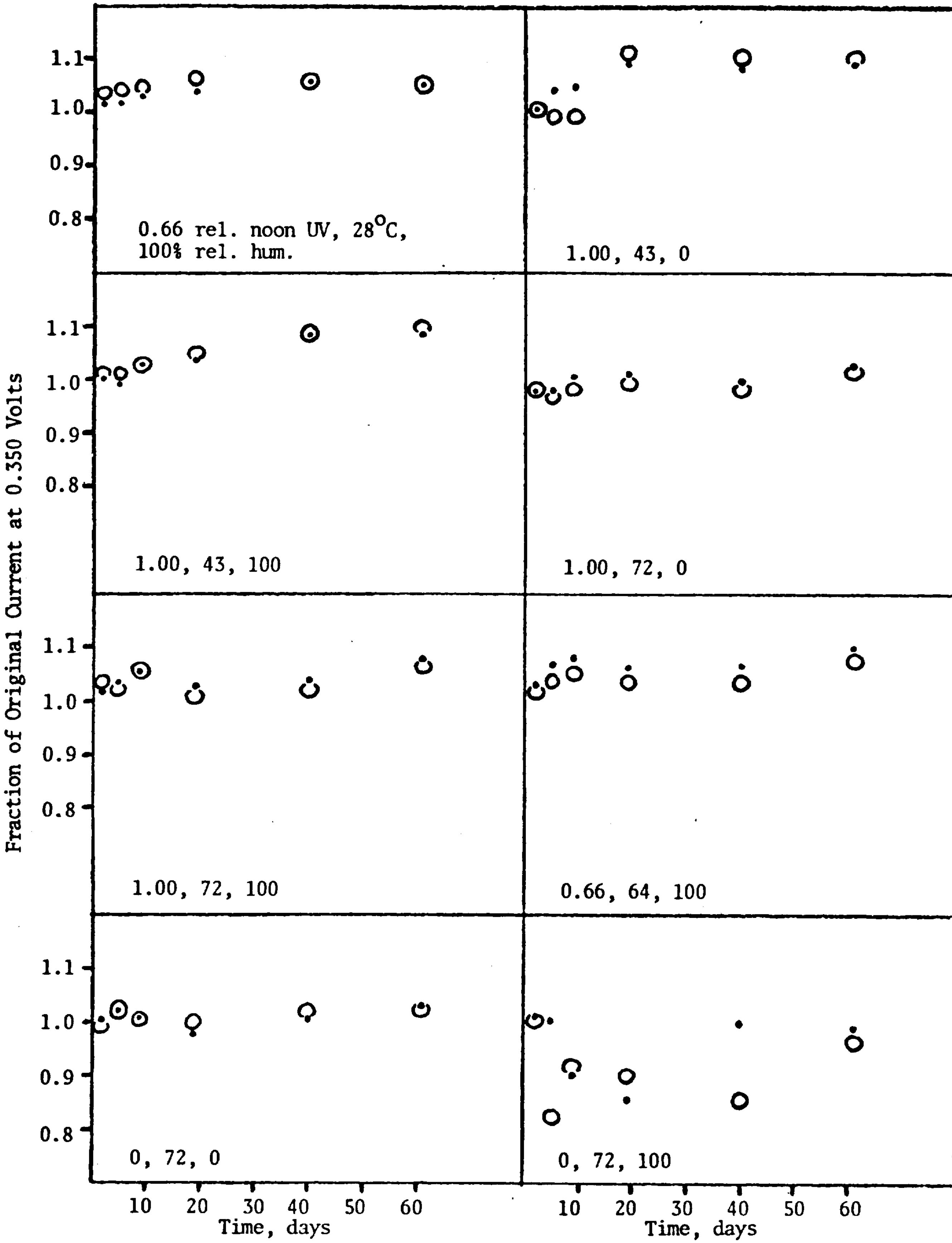
Figure 5. Change in Solar Cell Power
During Accelerated Exposure:
Array System 2*



*Encapsulant: Parylene C, Substrate: ceramic, Circuitry: Mo/Mn + Cu

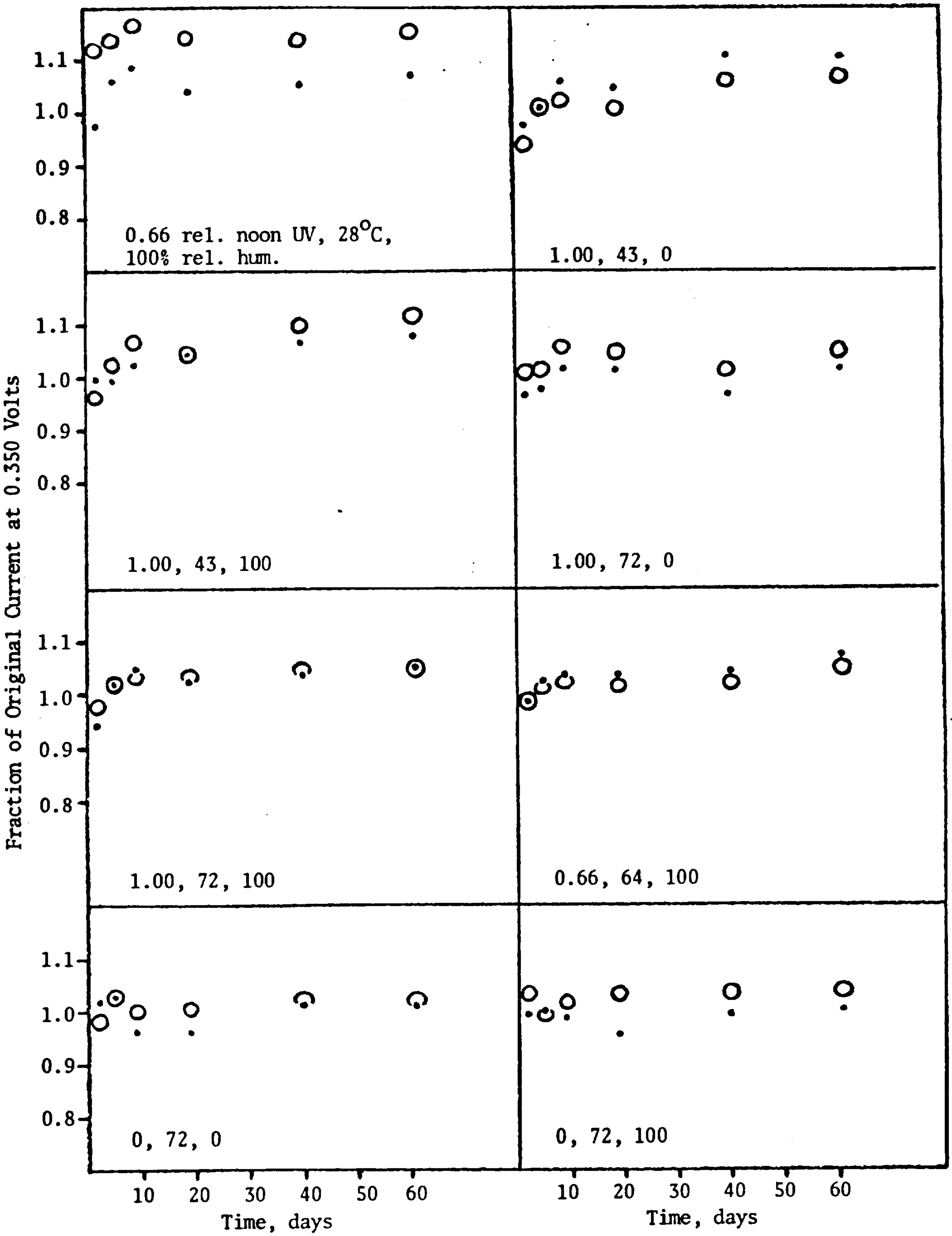
• = Cell 2, O = Cell 5

Figure 6. Change in Solar Cell Power During Accelerated Exposure: Array System 3*



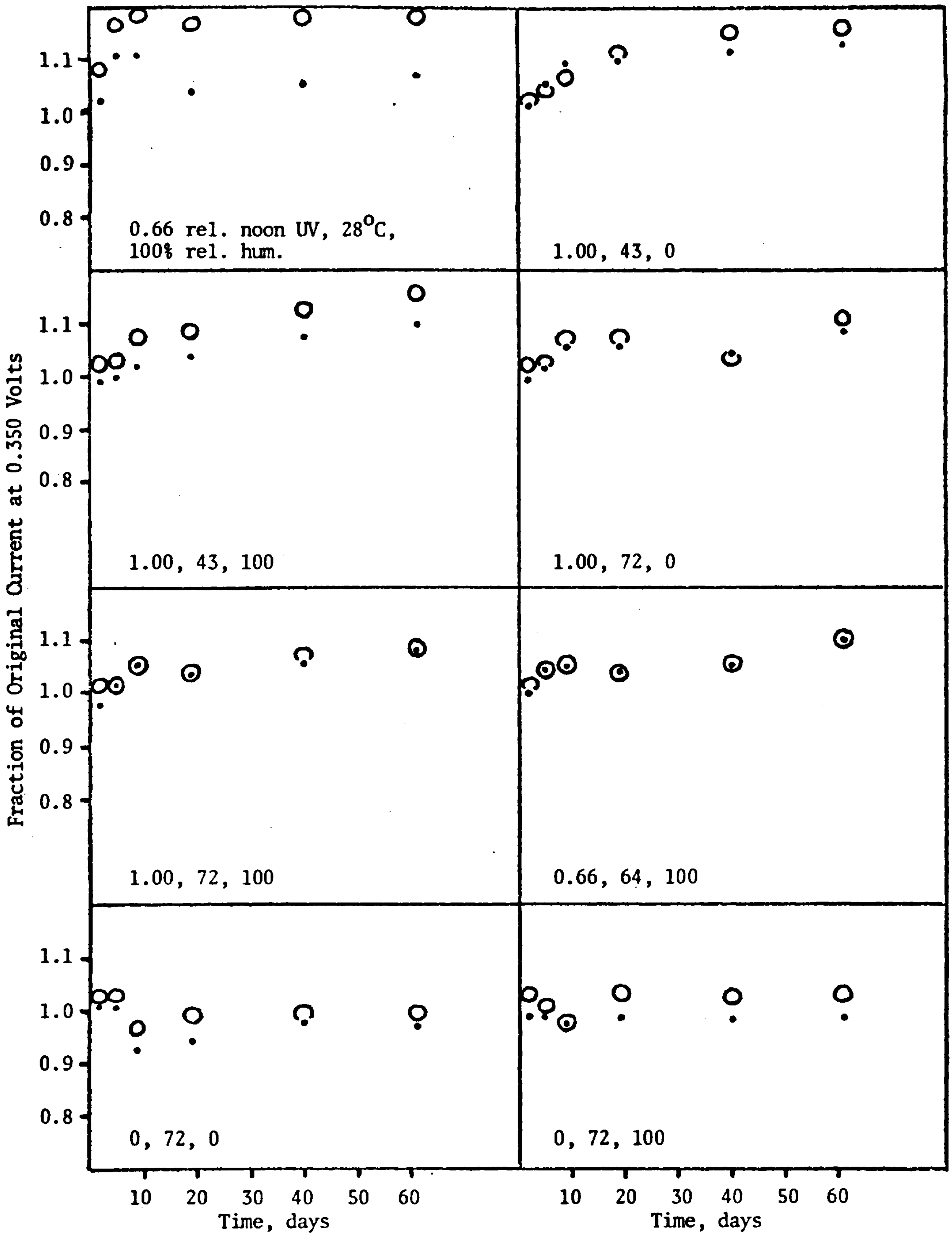
*Encapsulant: 2B74 + glass, Substrate: ceramic, Circuitry: Mo/Mn + Cu
• = Cell 1, O = Cell 4

Figure 7. Change in Solar Cell Power During Accelerated Exposure: Array System 4*



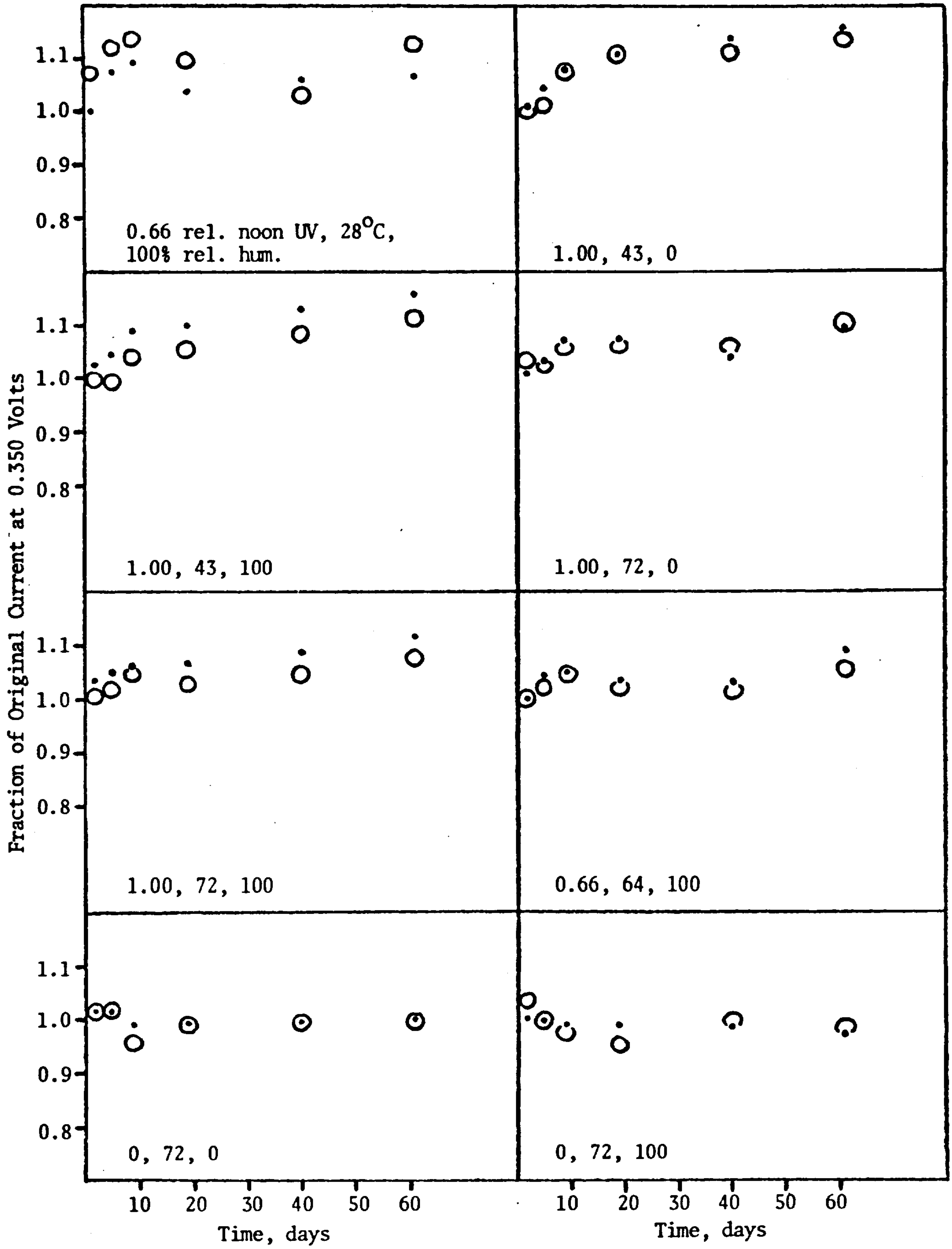
*Encapsulant: acrylic, Substrate: enameled steel, Circuitry: Cu (fired)
• = Cell 3, O = Cell 6

Figure 8. Change in Solar Cell Power
During Accelerated Exposure:
Array System 5*



*Encapsulant: Sylgard 184, Substrate: enameled steel, Circuitry: Cu (fired)
• = Cell 2, O = Cell 5

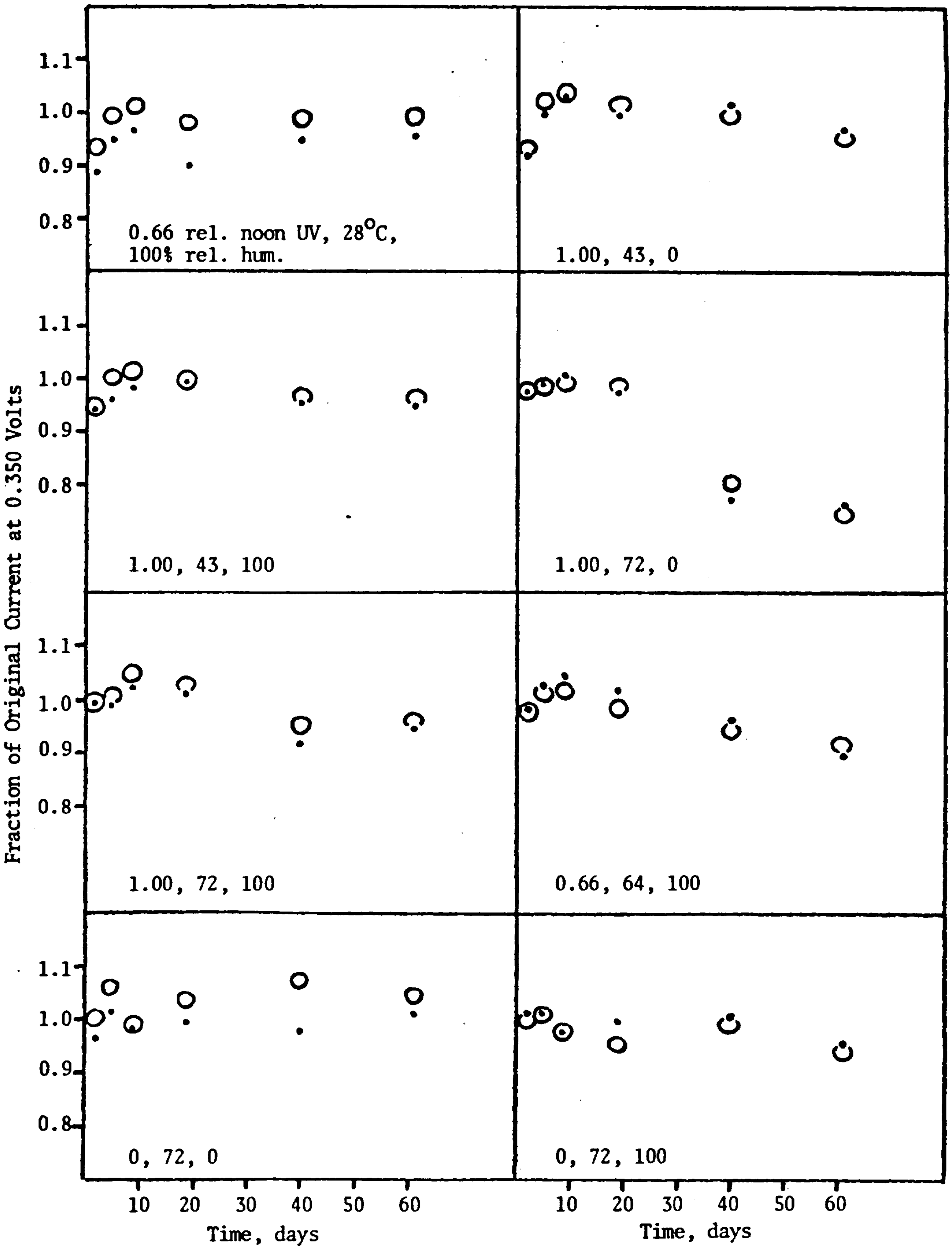
Figure 9. Change in Solar Cell Power During Accelerated Exposure: Array System 6*



*Encapsulant: 2B74 + glass, Substrate: enameled steel, Circuitry: Cu (fired)

• = Cell 1, O = Cell 4

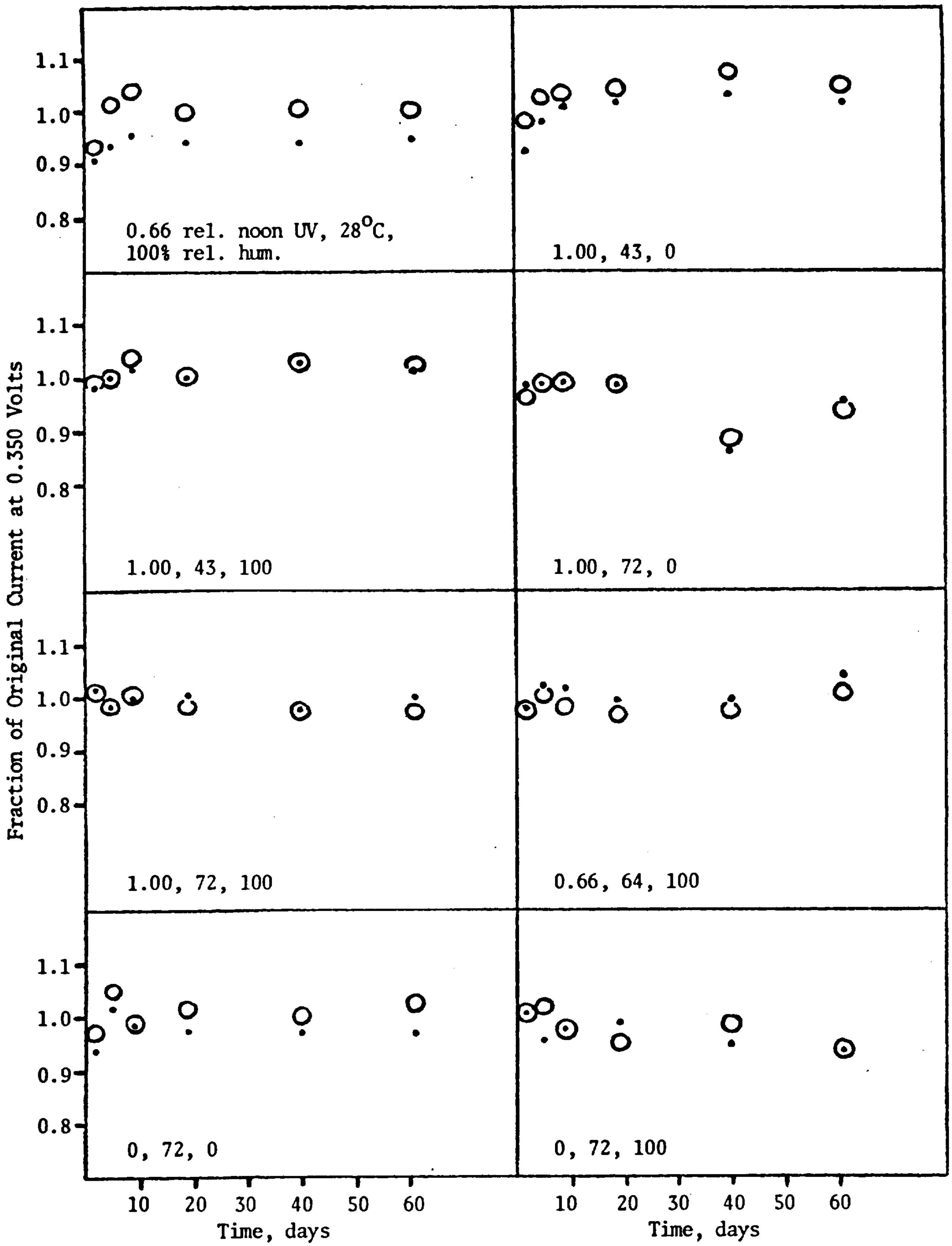
Figure 10. Change in Solar Cell Power During Accelerated Exposure: Array System 7*



*Encapsulant: nitrocellulose lacquer, Substrate: epoxy, Circuitry: Cu

• = Cell 3, O = Cell 6

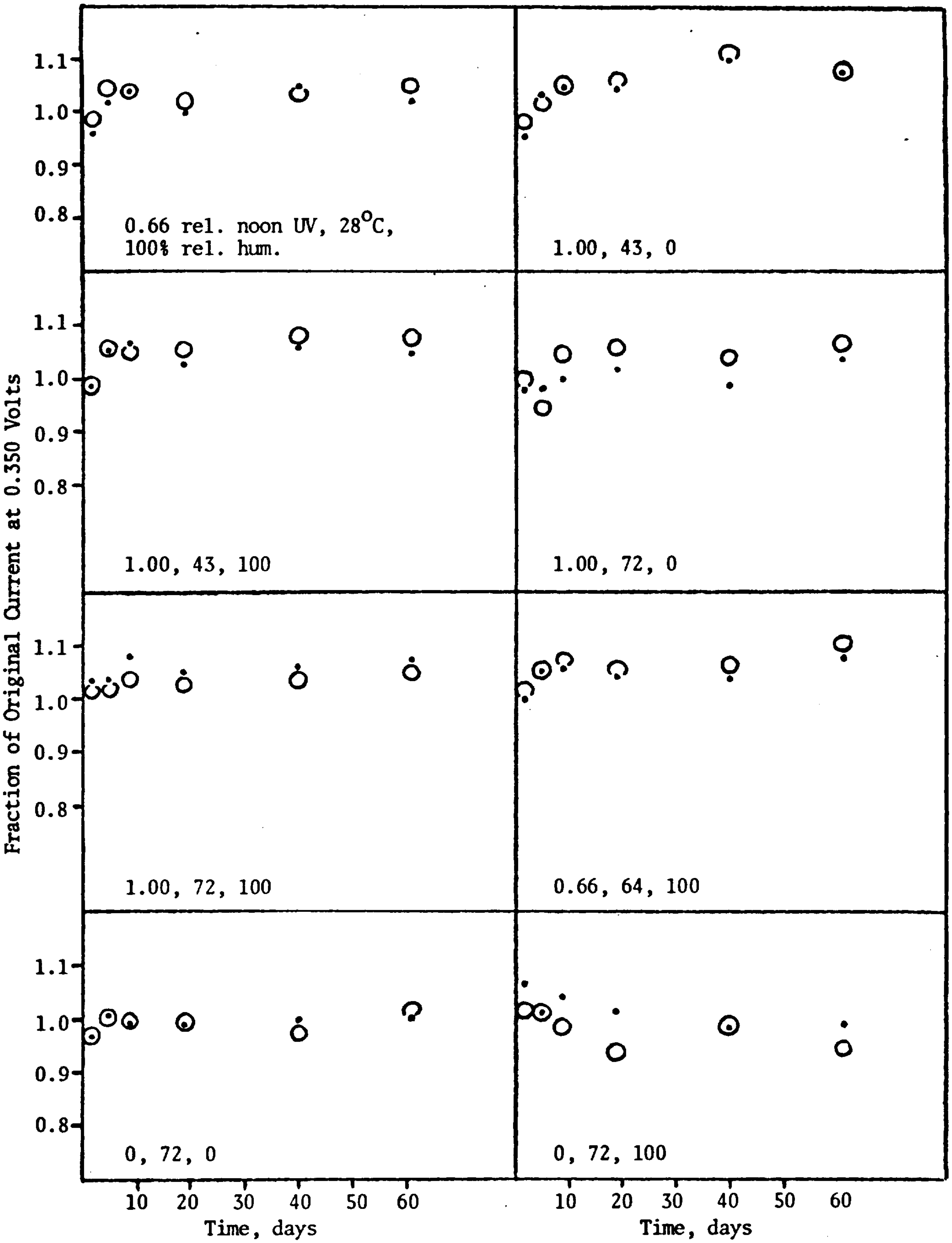
Figure 11. Change in Solar Cell Power During Accelerated Exposure: Array System 8*



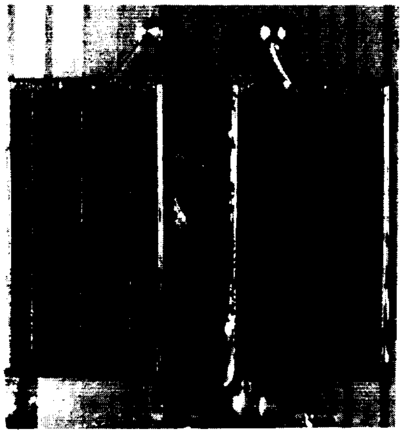
*Encapsulant: 2B74, Substrate: epoxy, Circuitry: Cu

• = Cell 2, O = Cell 5

Figure 12. Change in Solar Cell Power During Accelerated Exposure: Array System 9*



*Encapsulant: 2B74 + glass, Substrate: epoxy, Circuitry: Cu
• = Cell 1, O = Cell 4

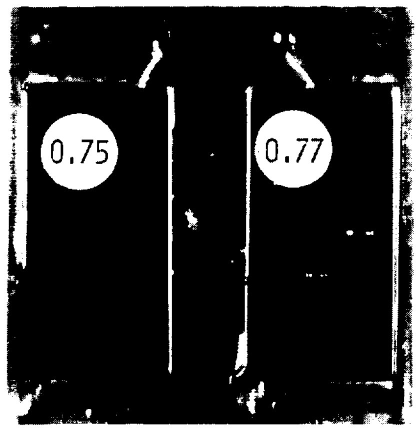


UNEXPOSED

0.66 REL. UV,
28^{o}C, 100% R.H.

1.00 REL. UV,
43^{o}C, 0% R.H.

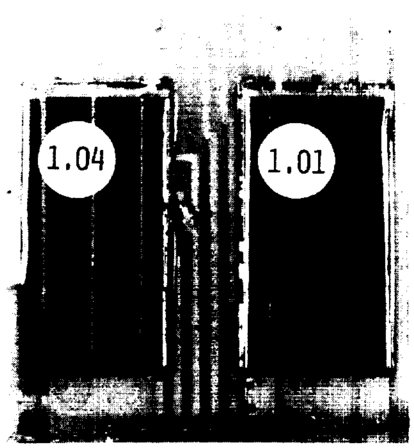
1.00 REL. UV,
43^{o}C, 100% R.H.



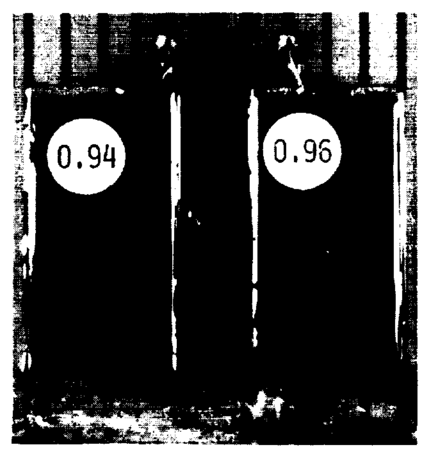
1.00 REL. UV,
72^{o}C, 0% R.H.

1.00 REL. UV,
72^{o}C, 100% R.H.

0.66 REL. UV,
64^{o}C, 100% R.H.



0 REL. UV,
72^{o}C, 0% R.H.



0 REL. UV,
72^{o}C, 100% R.H

FIGURE 13. ENCAPSULANT SYSTEM #7 (NITROCELLULOSE LACQUER ENCAPSULANT, EPOXY SUBSTRATE) AFTER 61 DAYS ACCELERATED EXPOSURE
NOTE: FRACTION OF ORIGINAL POWER IS SHOWN FOR EACH CELL.

Figure 14. Encapsulant System #7 (Nitrocellulose Lacquer, Epoxy Substrate) After 61 Days Accelerated Exposure.
Conditions: 0.66 UV, 64°C, 100% R.H., Magnified 10X

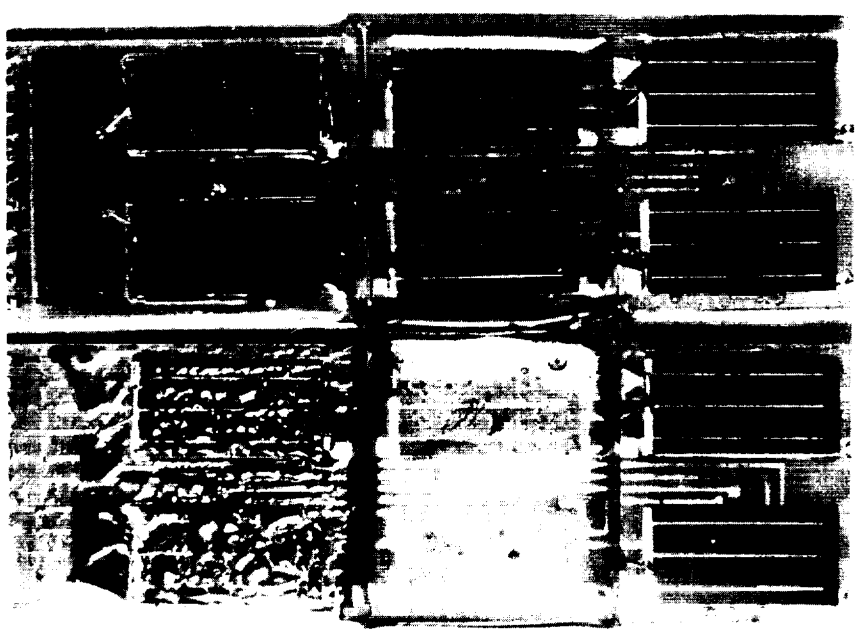
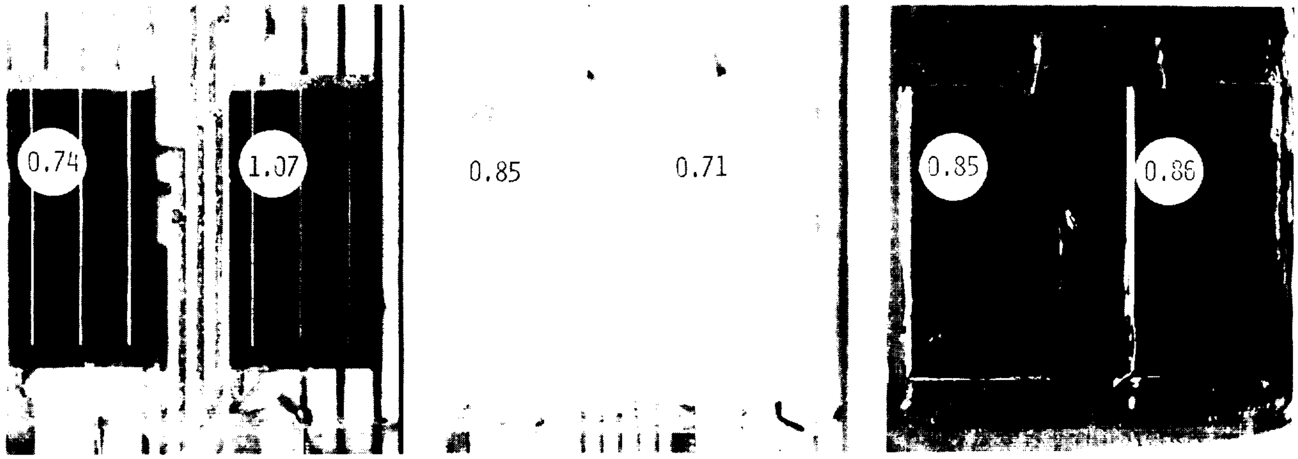
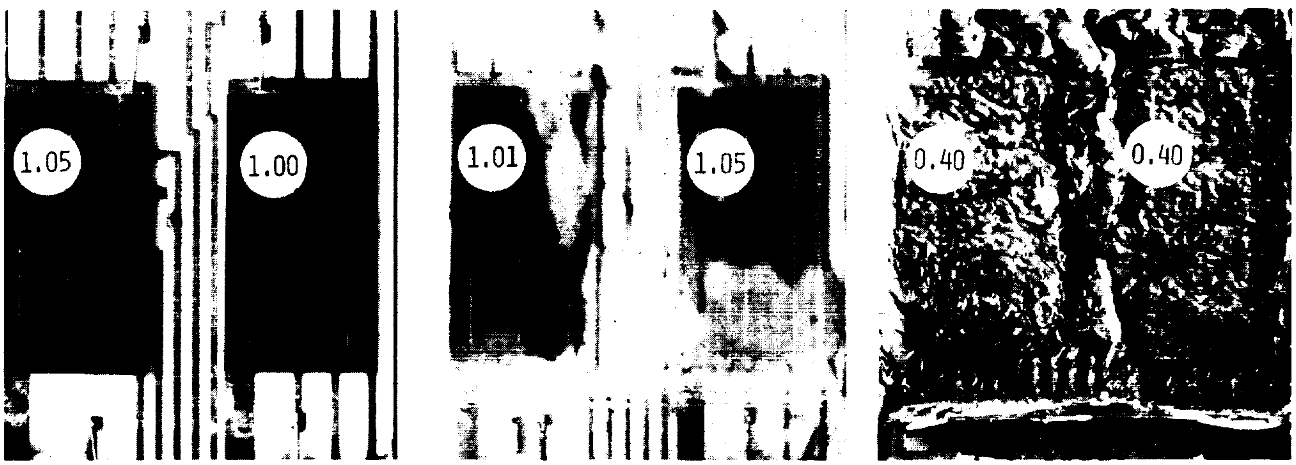


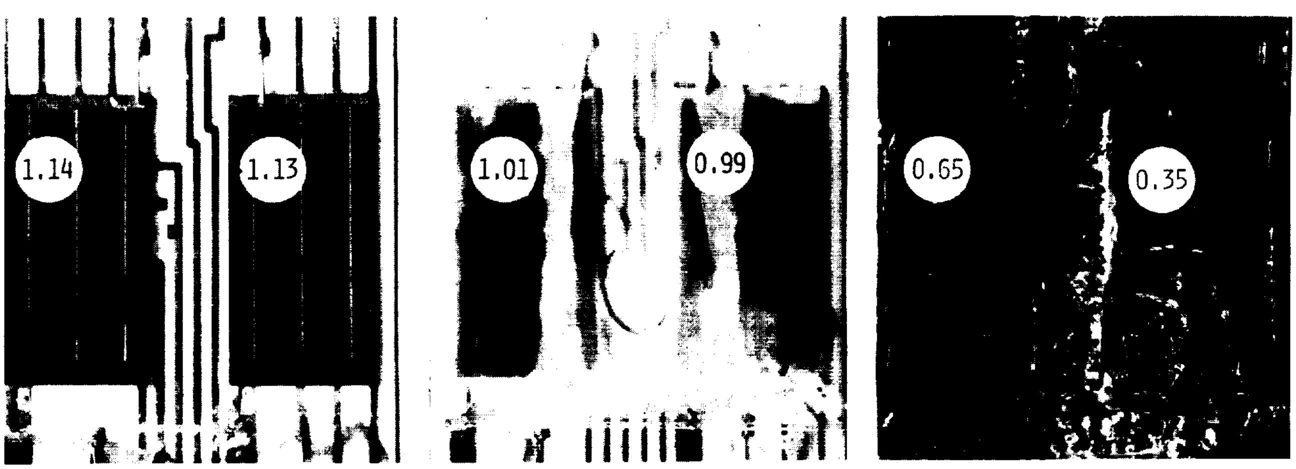
Figure 15. Encapsulant Systems #7-9 (Epoxy Substrate) After 61 Days Accelerated Exposure.
Conditions: 1.00 Rel. UV, 72°C.
Above: 0% R.H. Below: 100% R.H.
Encapsulant Covers, left to right: nitrocellulose lacquer, 2B74, 2B74 + glass.



0.66 Rel. UV, 28°C, 100% R.H.

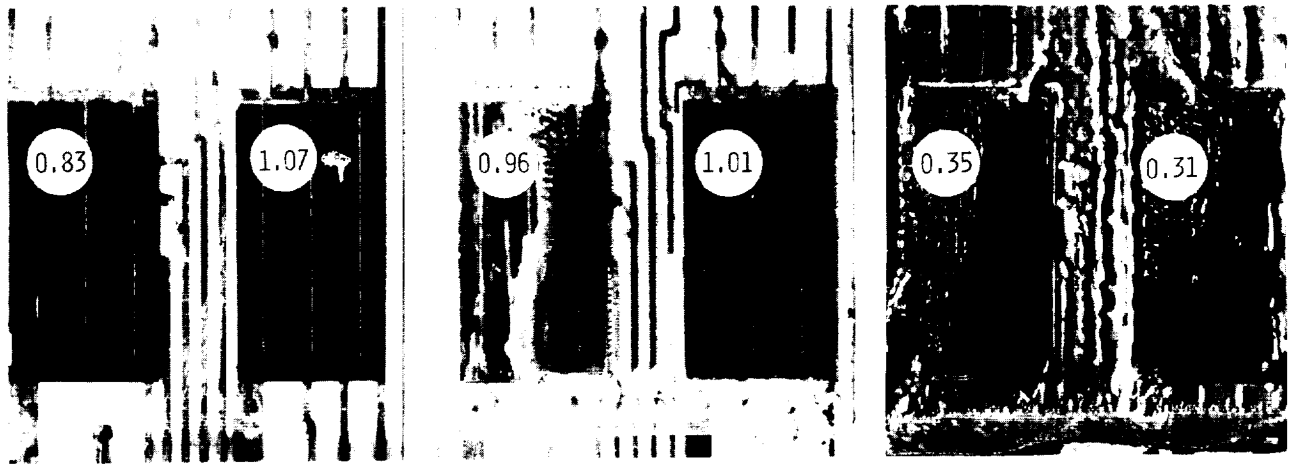


1.00 Rel. UV, 43°C, 0% R.H.



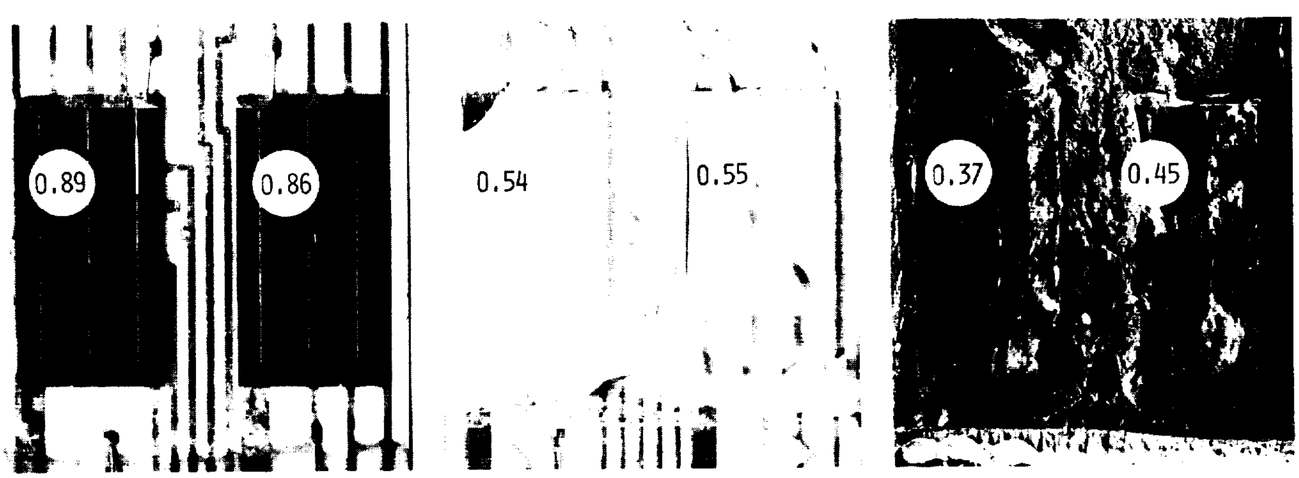
1.00 Rel. UV, 43°C, 100% R.H.

Figure 16. Encapsulant Systems After 61 Days Accelerated Exposure Followed by 12 Days Steam Exposure.
Left: System #1 (no cover, ceramic substrate)
Center: System #4 (acrylic lacquer, enameled steel substrate)
Right: System #7 (nitrocellulose lacquer, epoxy substrate)
NOTE: Fraction of original power is shown for each cell.



1.00 Rel. UV, 72°C, 0% R.H.

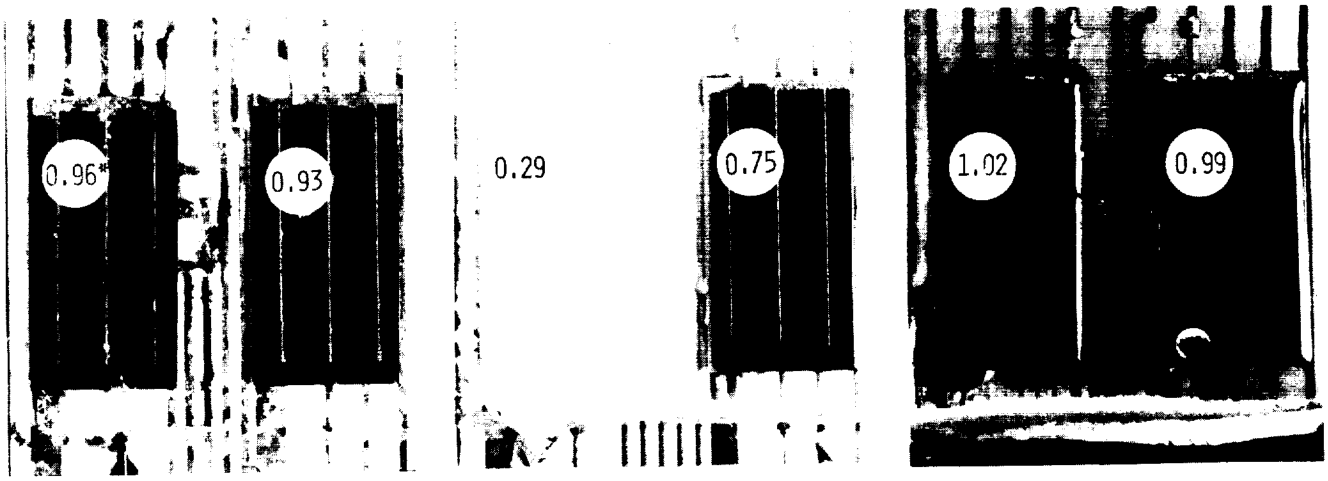
1.00 Rel. UV, 72°C, 100% R.H.



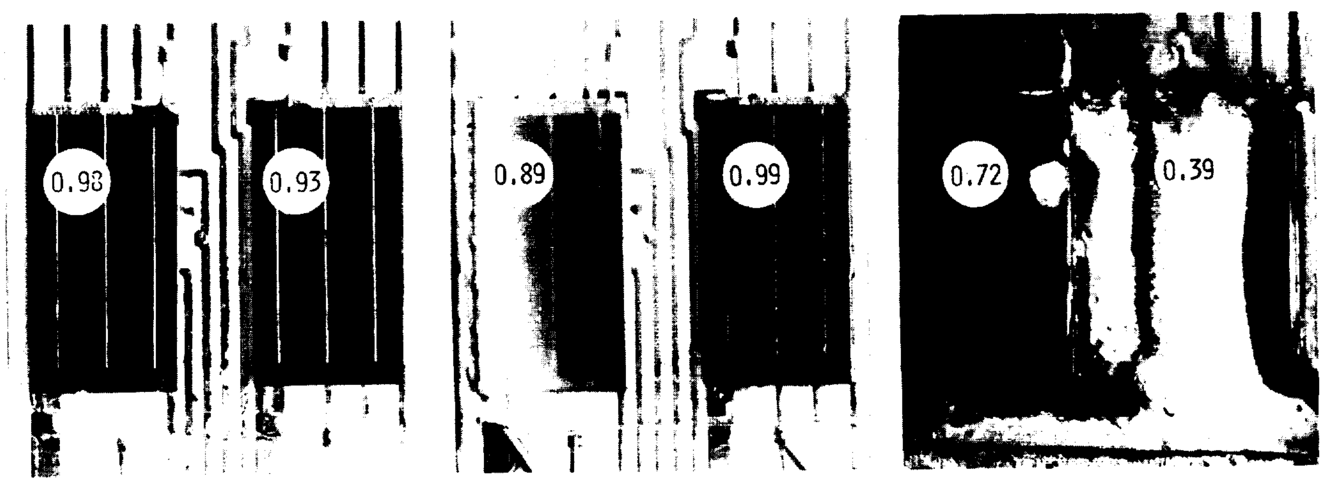
0.66 Rel. UV, 64°C, 100% R.H.

*By probing

Figure 16. Continued



0 Rel. UV, 72°C, 0% R.H.

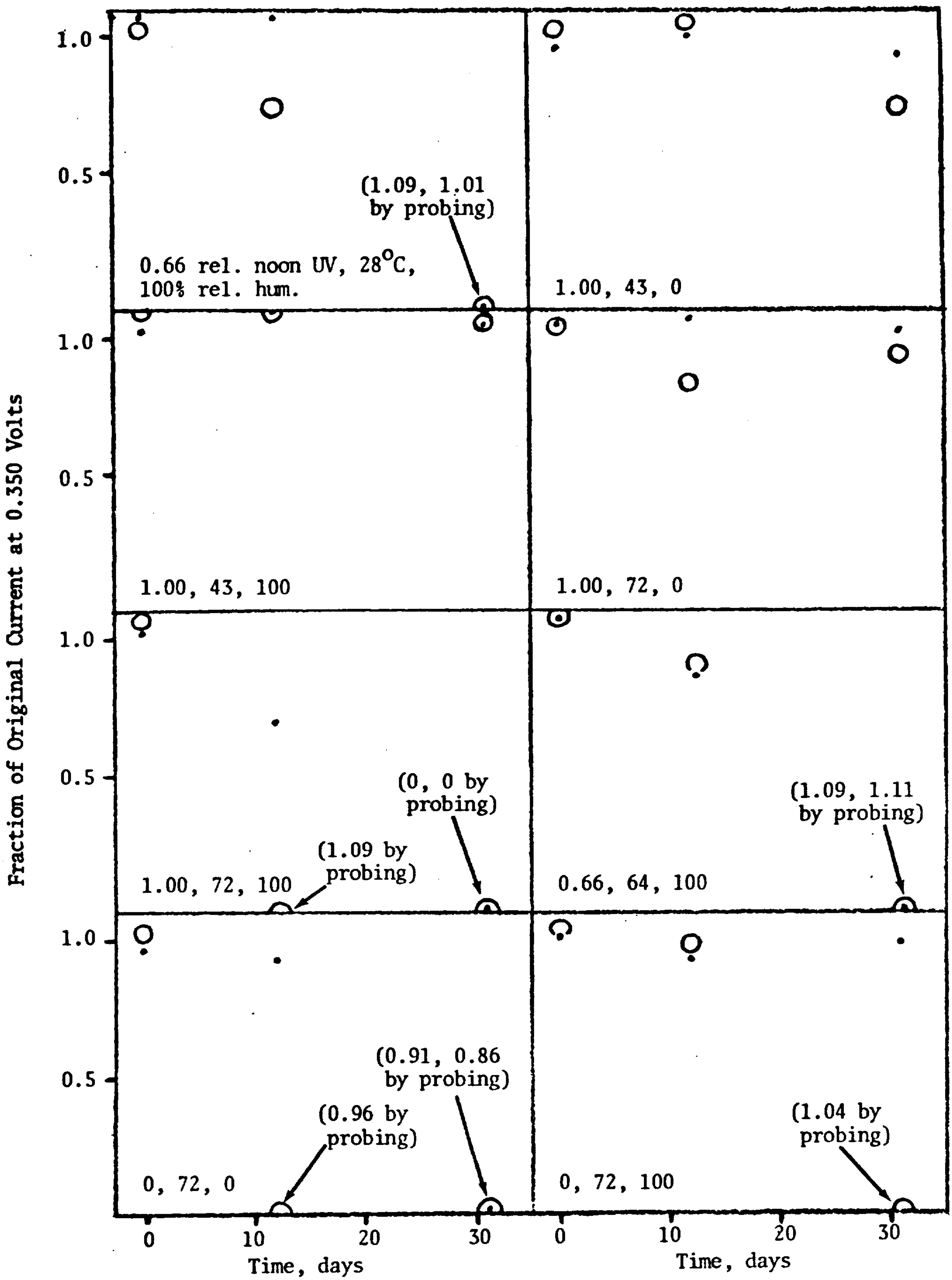


0 Rel. UV, 72°C, 100% R.H.

Figure 16. Continued

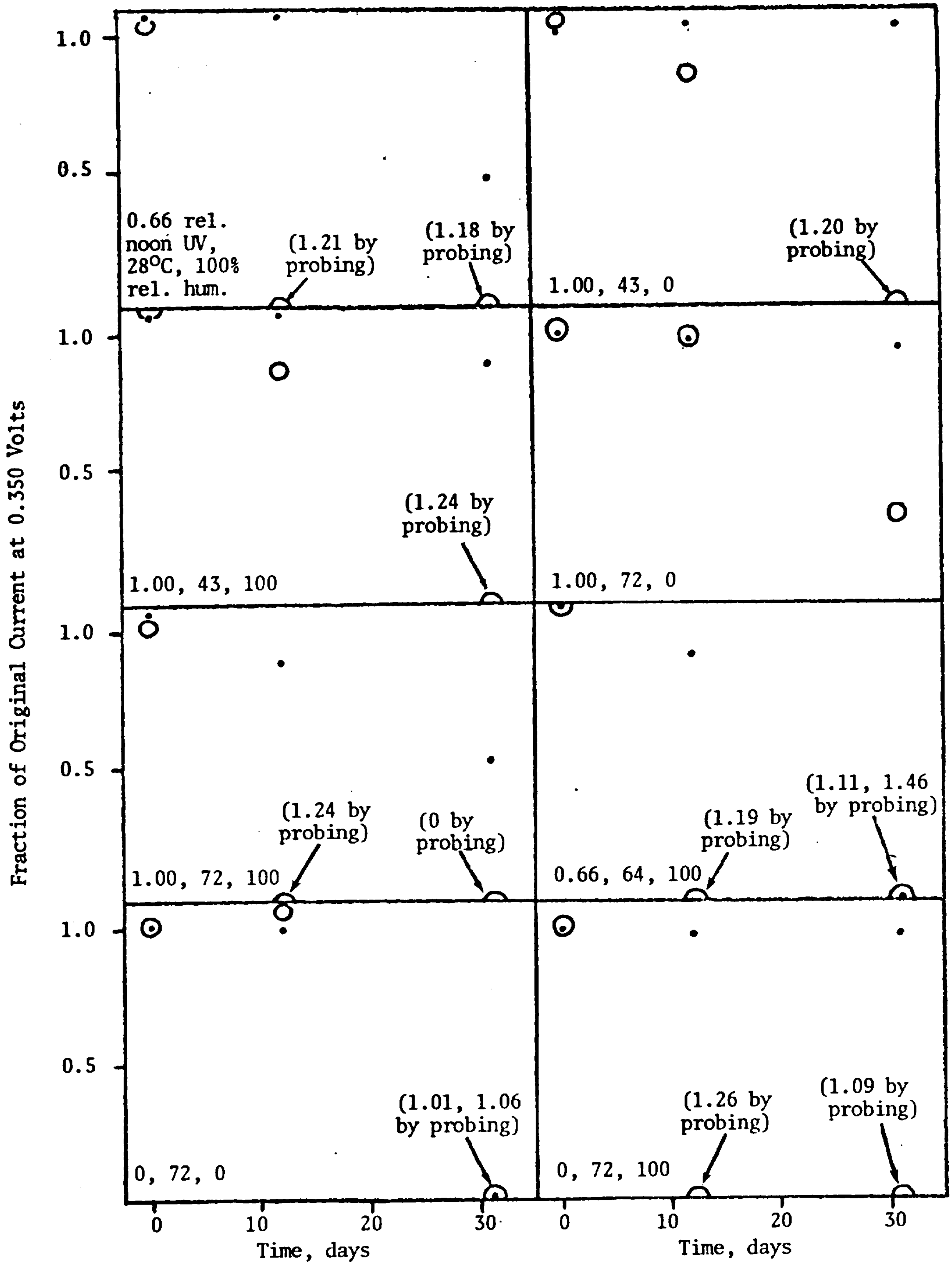
*By probing

Figure 17. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 1*



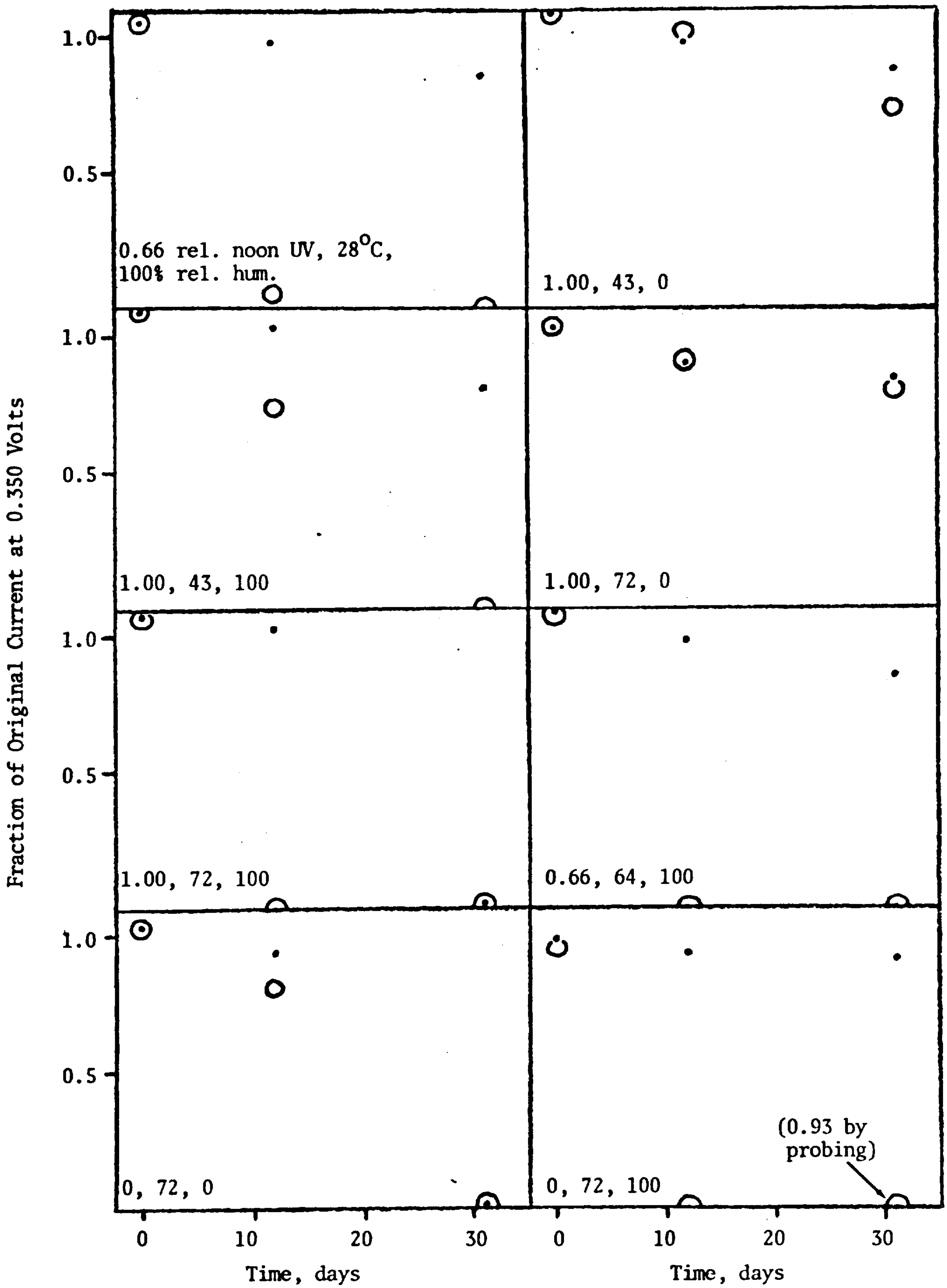
*Encapsulant: none, Substrate: ceramic, Circuitry: Mo/Mn + Cu
• = Cell 3, O = Cell 6

Figure 18. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 2*



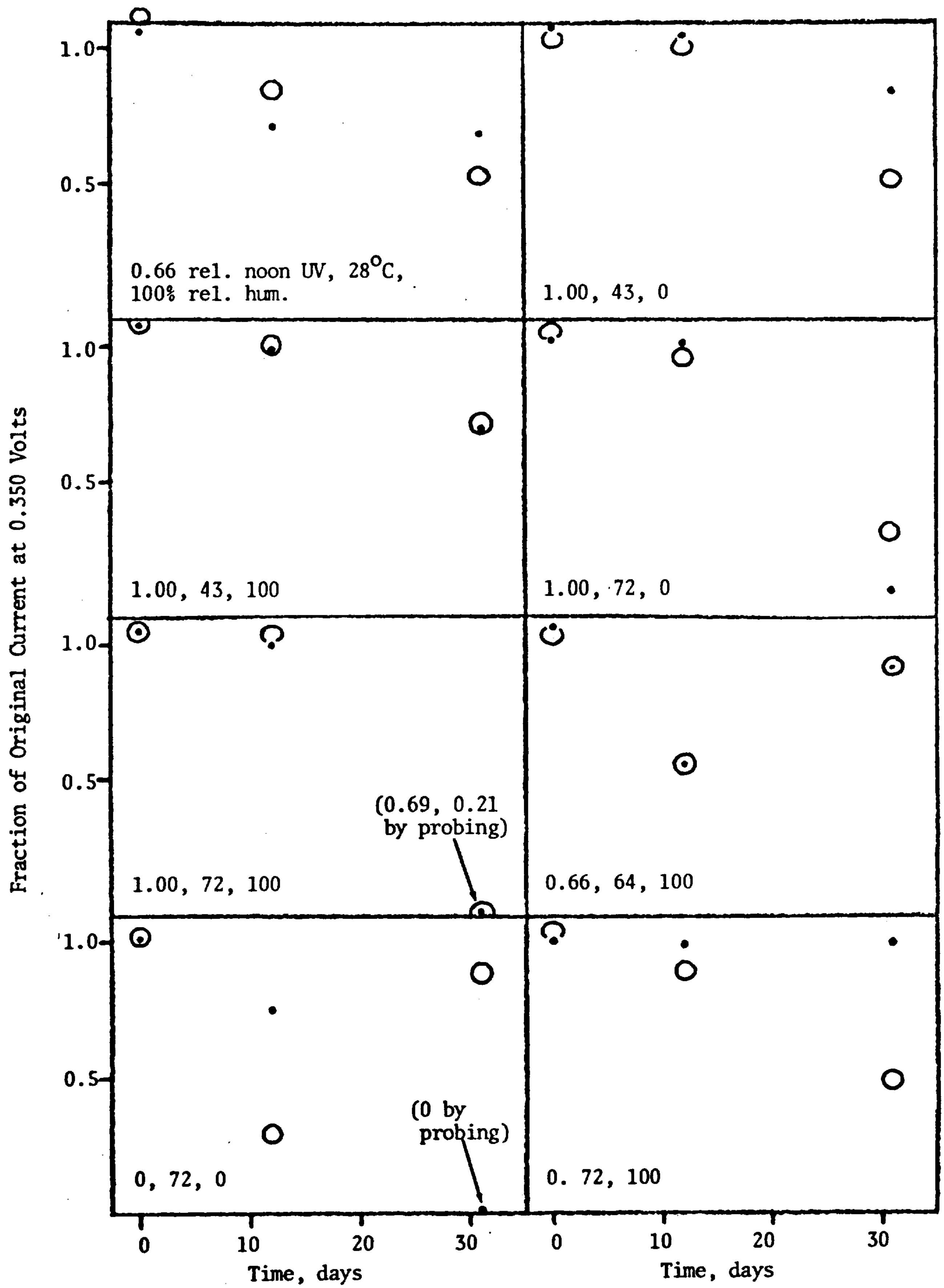
*Encapsulant: Parylene C, Substrate: ceramic, Circuitry: Mo/Mn + Cu
• = Cell 2, O = Cell 5

Figure 19. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 3*



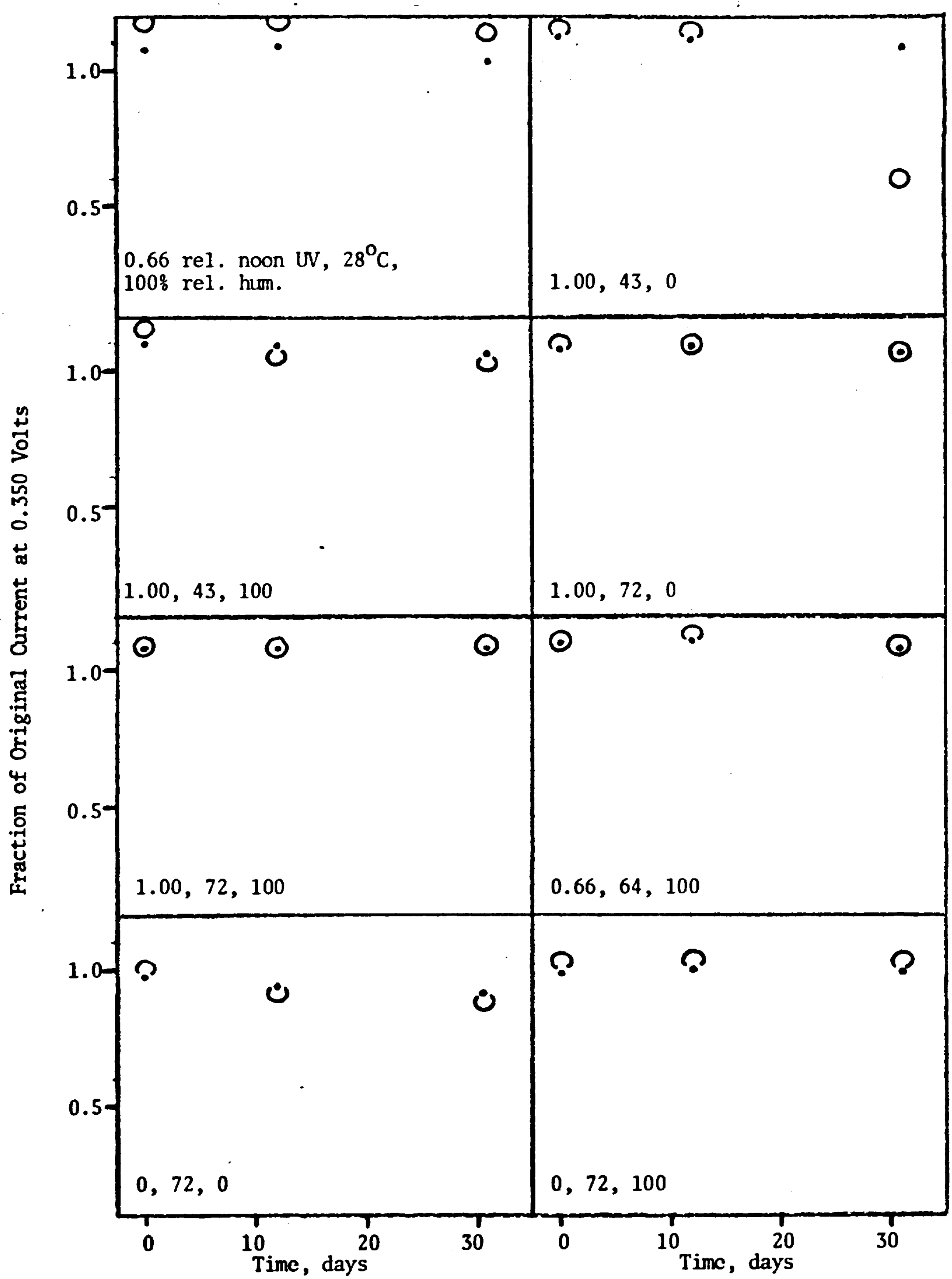
*Encapsulant: 2B74 + glass, Substrate: ceramic, Circuitry: Mo/Mn + Cu
• = Cell 1, O = Cell 4

Figure 20. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 4*



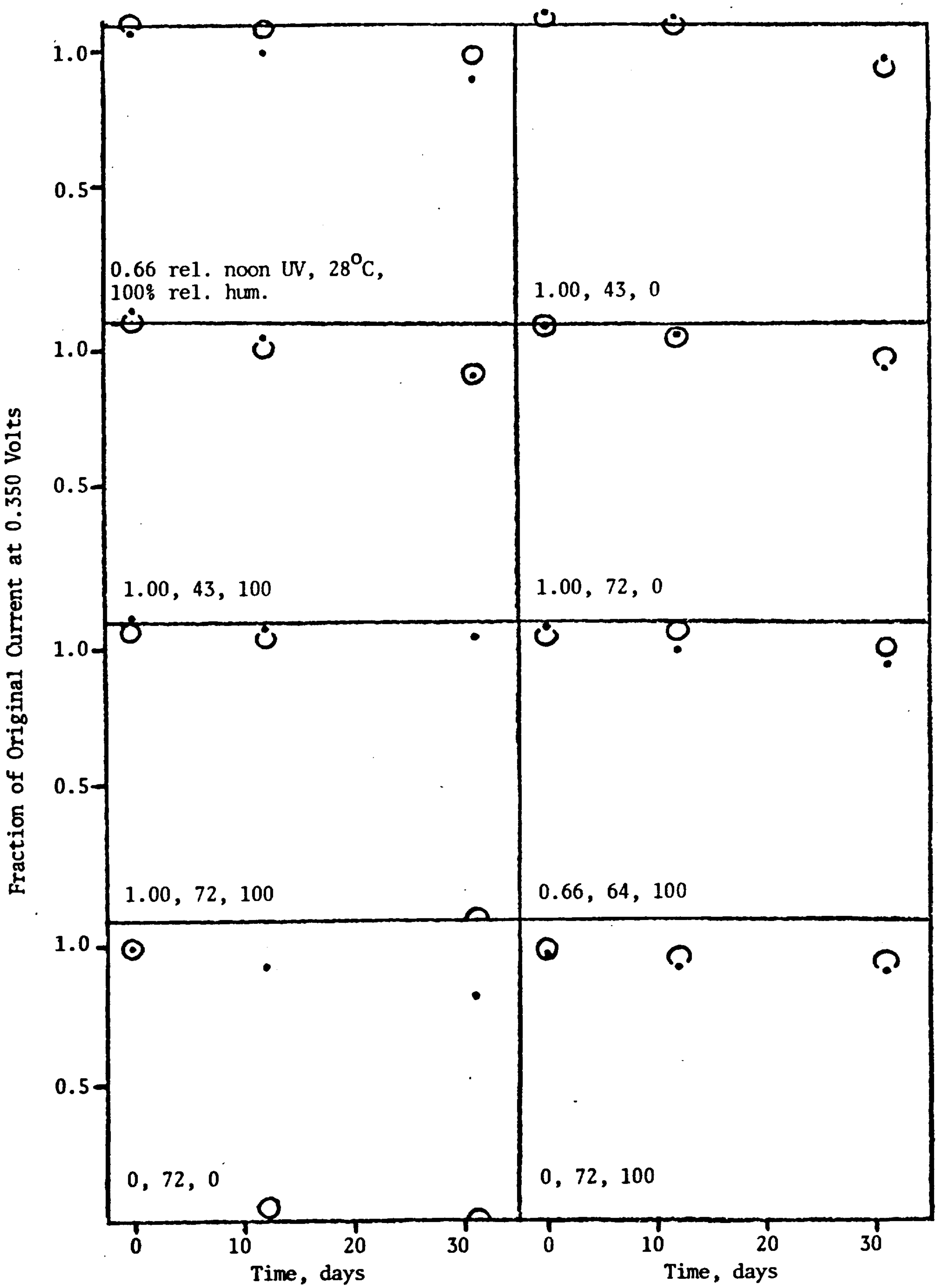
*Encapsulant: acrylic, Substrate: enameled steel, Circuitry: Cu (fired)
• = Cell 3, O = Cell 6

Figure 21. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 5*



*Encapsulant: Sylgard 184, Substrate: enameled steel, Circuitry: Cu (fired)
• = Cell 2, O = Cell 5

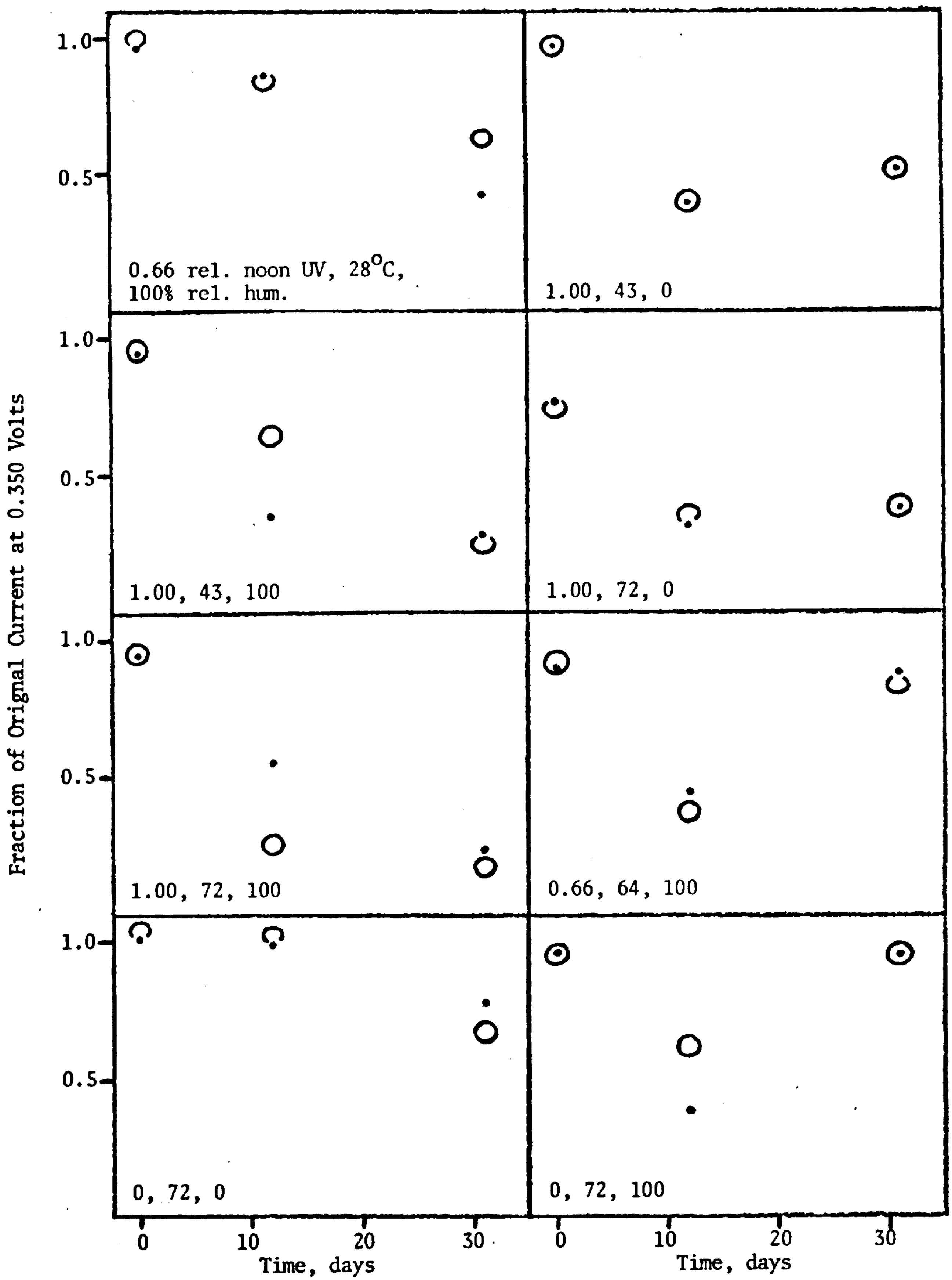
Figure 22. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 6*



*Encapsulant: 2B74 + glass, Substrate: enameled steel, Circuitry: Cu (fired)

• = Cell 1, O = Cell 4

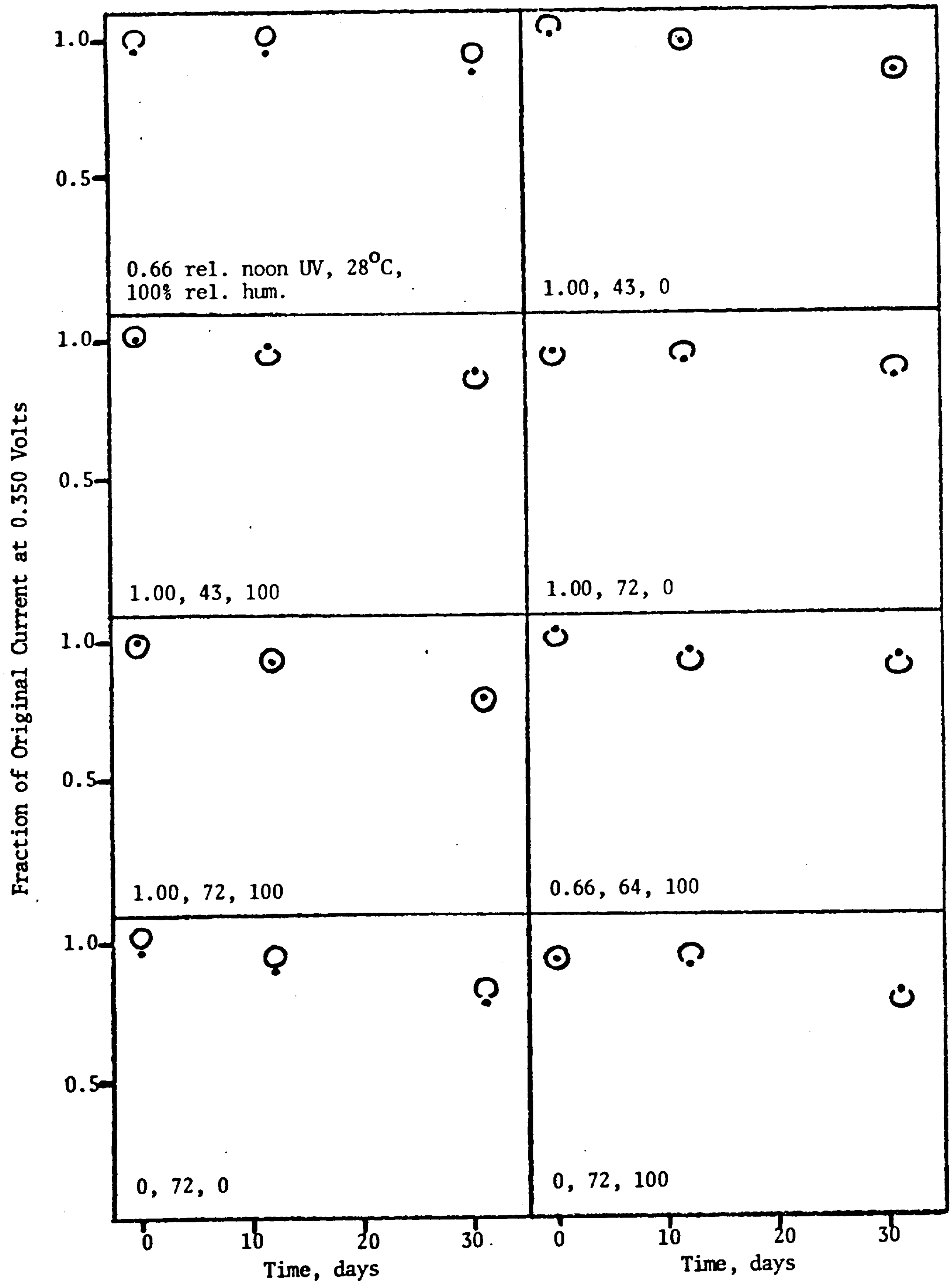
Figure 23. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 7*



*Encapsulant: nitrocellulose lacquer, Substrate: epoxy, Circuitry: Cu

• = Cell 3, O = Cell 6

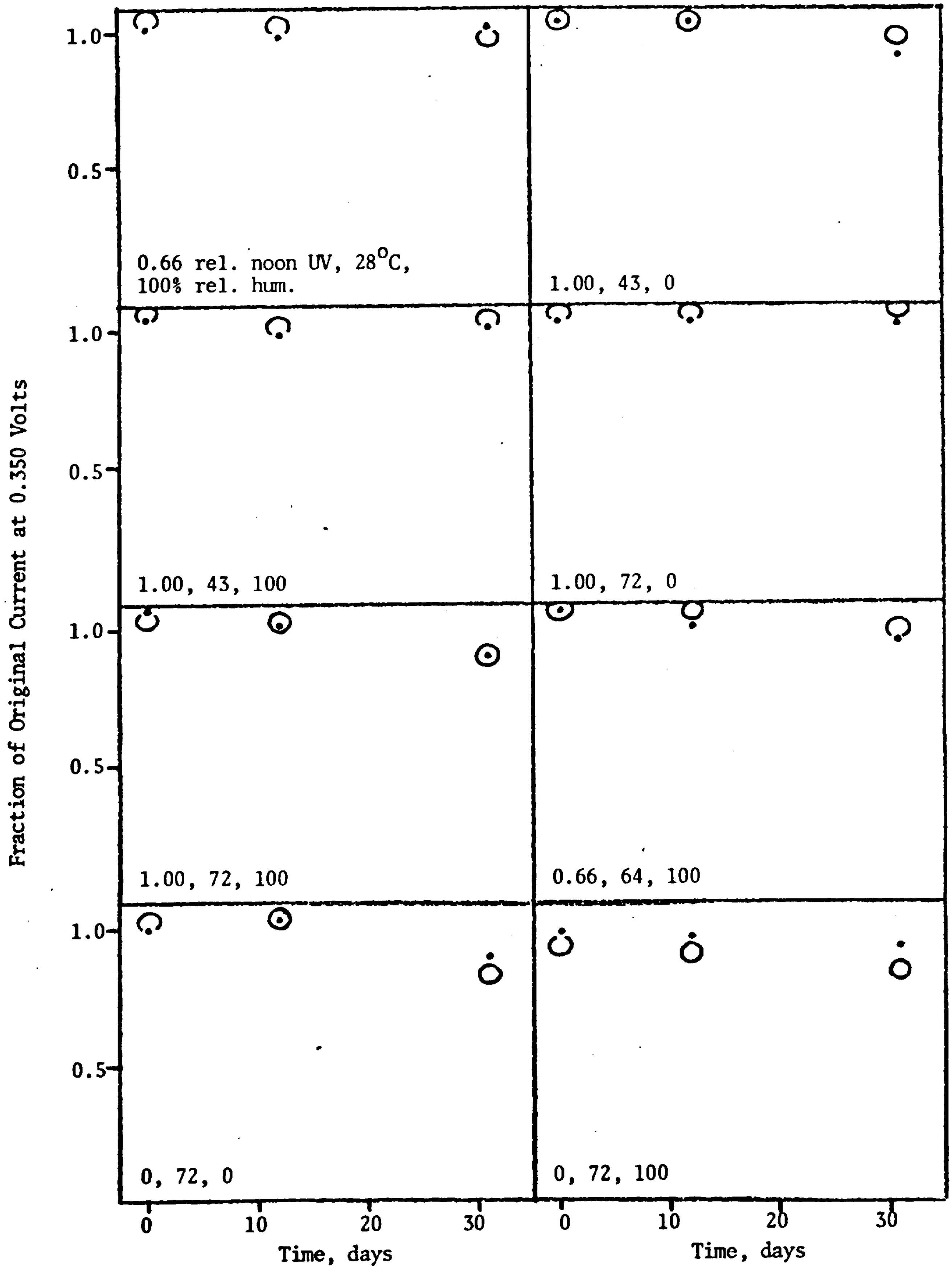
Figure 24. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 8*



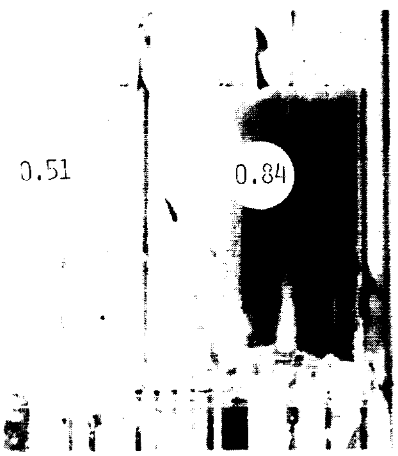
*Encapsulant: 2B74, Substrate: epoxy, Circuitry: Cu

• = Cell, O = Cell 5

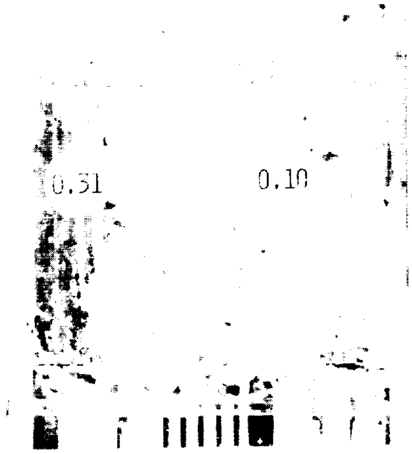
Figure 25. Change in Solar Cell Power During Steam Exposure Following 61 Days Accelerated Exposure: Array System 9*



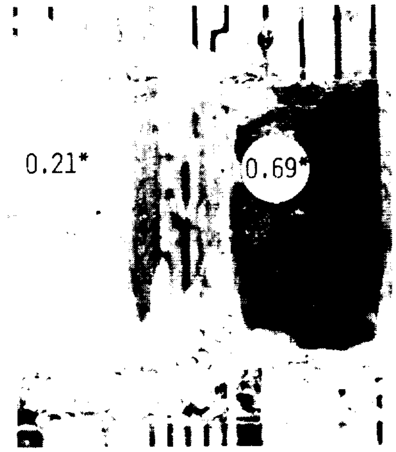
*Encapsulant: 2B74 + glass, Substrate: epoxy, Circuitry: Cu
• = Cell 1, O = Cell 4



SYSTEM #4
1.00 REL. UV, 43°C, 0% R.H.

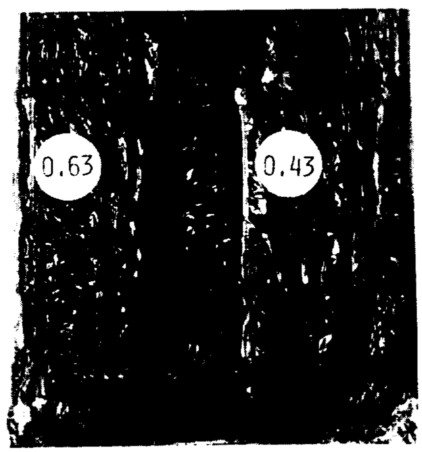


SYSTEM #4
1.00 REL. UV, 72°C, 0% R.H.

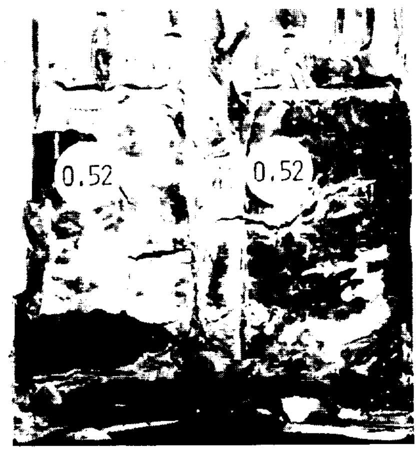


SYSTEM #4
1.00 REL. UV, 72°C, 100% R.H.

SYSTEM #4
0.66 REL. UV, 64°C, 100% R.H.



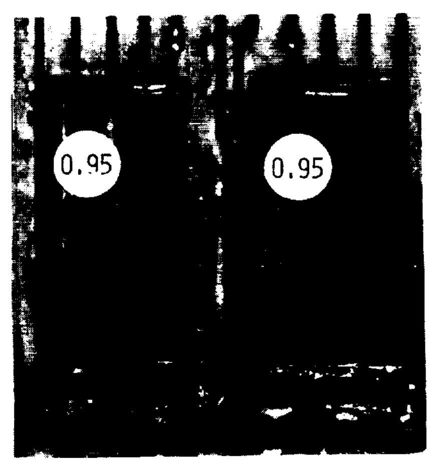
SYSTEM #7
0.66 REL. UV, 28°C, 100% R.H.



SYSTEM #7
1.00 REL. UV, 43°C, 0% R.H.

SYSTEM #7
0.66 REL. UV, 64°C, 100% R.H.

SYSTEM #7
0 REL UV, 72°C, 0% R.H.



SYSTEM #7
0 REL. UV, 72°C, 100% R.H.

FIGURE 26. ENCAPSULANT SYSTEMS AFTER 61 DAYS ACCELERATED EXPOSURE FOLLOWED BY 31 DAYS STEAM EXPOSURE.
SYSTEM #4: ACRYLIC LACQUER, ENAMELED STEEL SUBSTRATE
SYSTEM #7: NITROCELLULOSE LACQUER, EPOXY SUBSTRATE
NOTE: FRACTION OF ORIGINAL POWER IS SHOWN FOR EACH CELL.

*BY PROBING

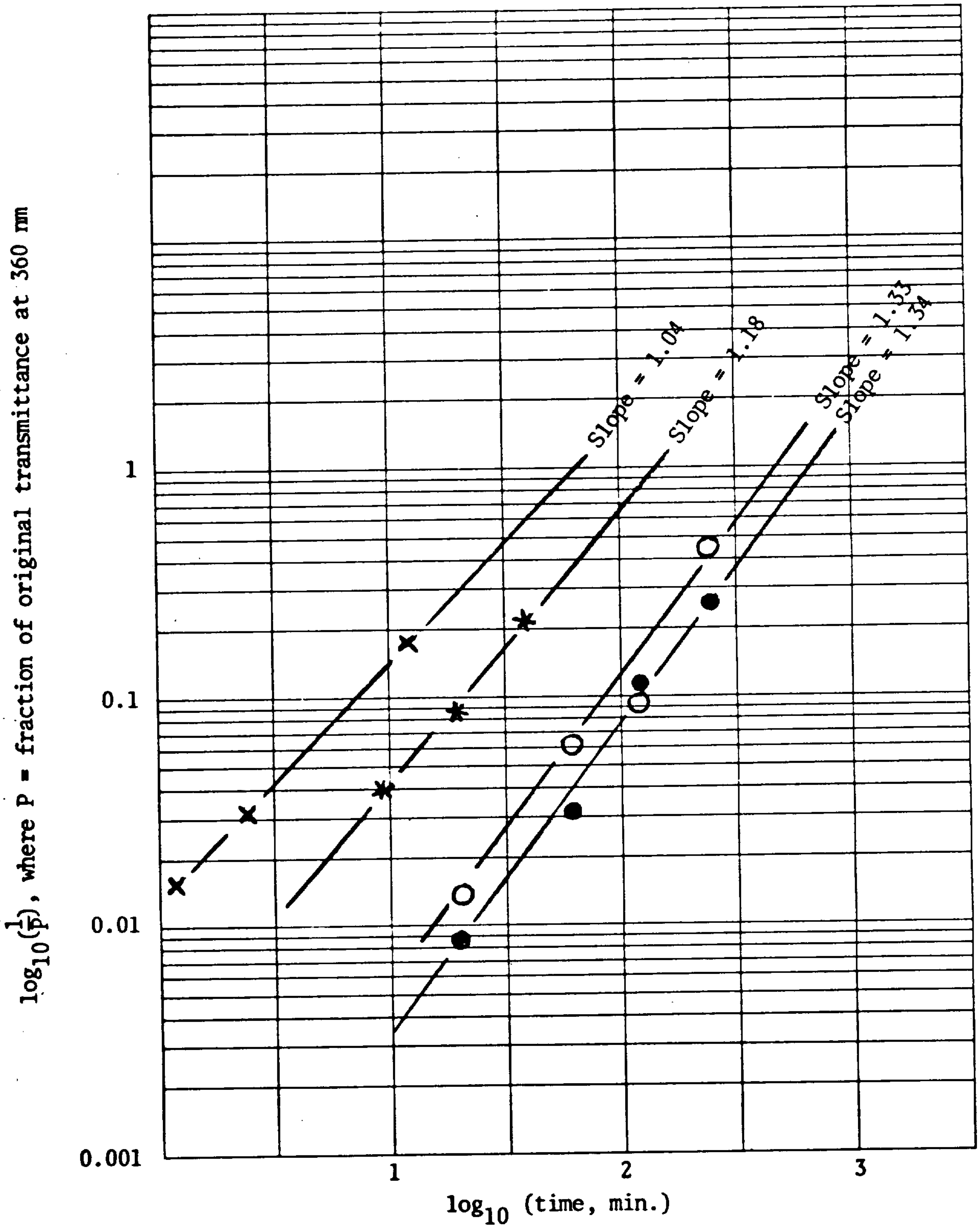


Figure 27. Increase in Absorbance of Plastic Films in Solar Furnace at 1400 Suns vs. Xenon Lamp at 1 Sun.

✕ Polystyrene exposed to xenon lamp (1.00 rel. noon UV, 26°C, 100% R.H.), arbitrary time sca

✱ Lexan exposed to xenon lamp (same basis).

○ Lexan in solar furnace, under water at 35°C, 33 cal./cm.²/sec. (about 1400 suns).

● Polystyrene in solar furnace (same basis).

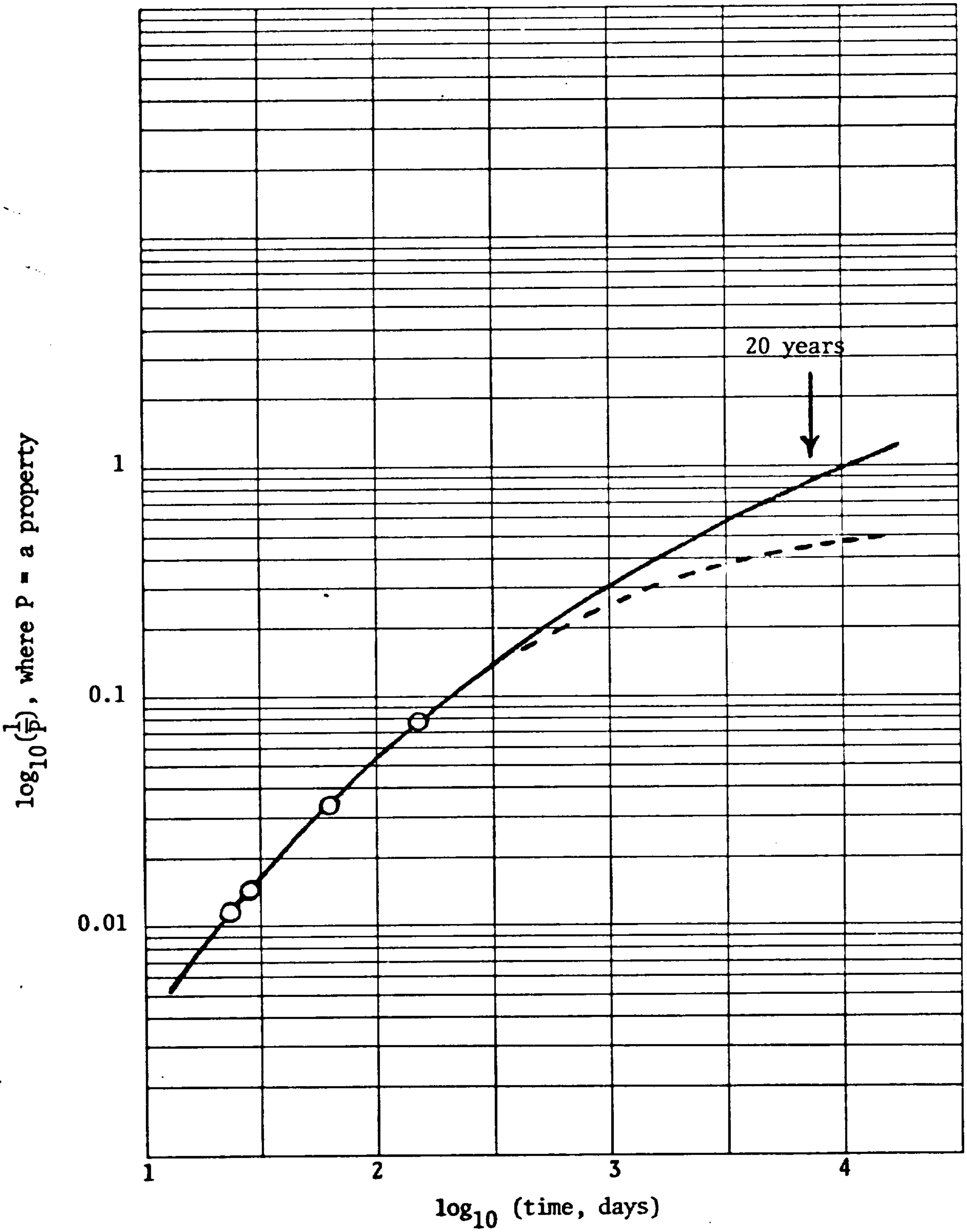


Figure 28. Hypothetical Data Points Extrapolated by Lognormal Model

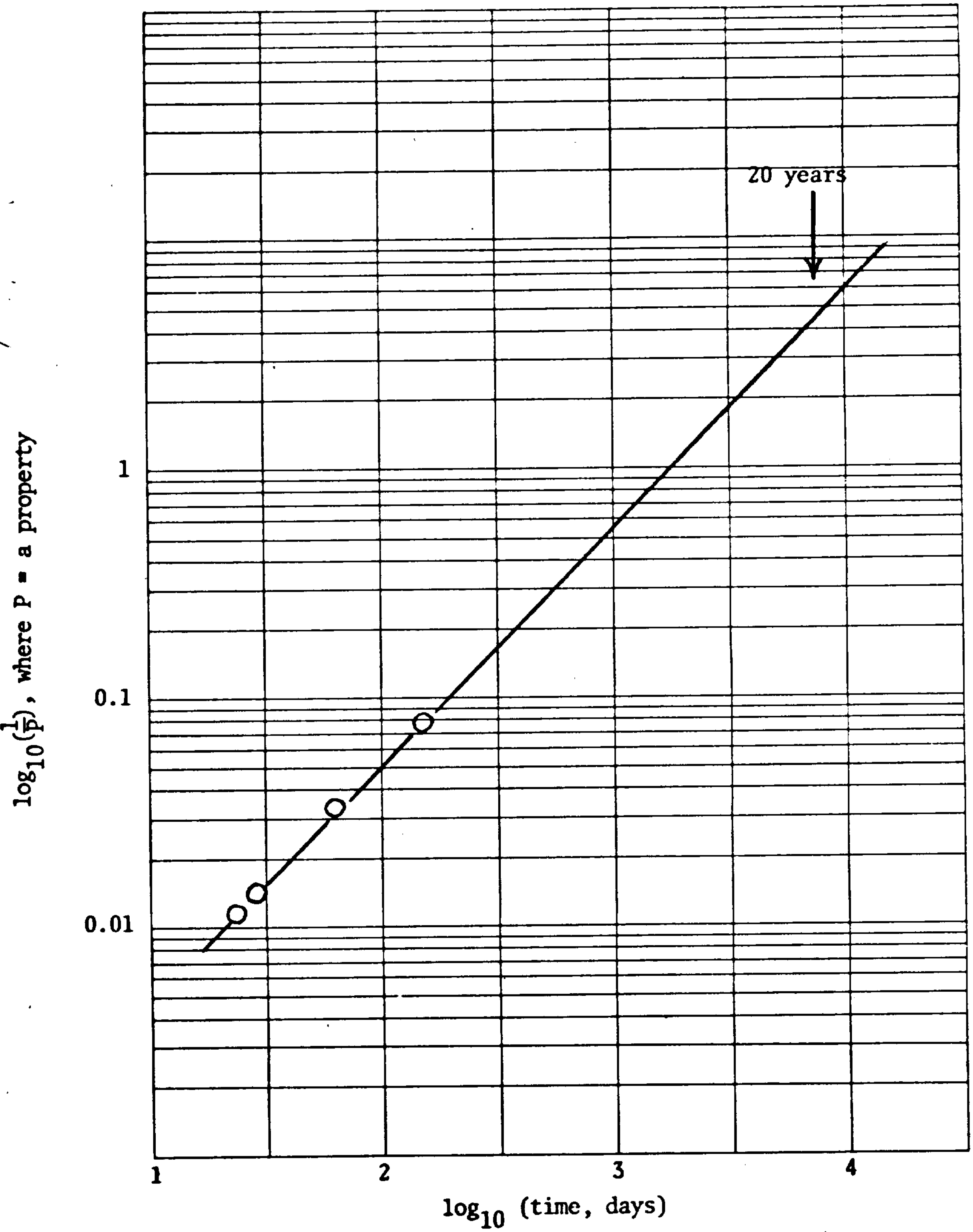


Figure 29. Hypothetical Data Points Extrapolated by Weibull Model

TABLE I

Monthly Rate Factors for Lexan Based on
Early Seasonal Absorbance Data

Exposure Site	Date Exposure Started	Early Exposure Data		Time, Days, to Reach $\log_{10}(\frac{1}{P})$* = 0.02	Monthly Rate Factor = Reciprocal of Last Column Divided by 0.0187
		$\log_{10}(\frac{1}{P})$*	Time, Days		
Phoenix	12/22	0.0224	60	54	1.0
	9/12	0.0271	30	22	2.4
	6/21	0.0195	15	15	3.6
Miami	12/22	0.0340	60	35	1.5
	9/1	0.0269	30	22	2.4
	6/21	0.0302	30	20	2.7

*where P = fraction of original transmittance at 360 nm.

TABLE II

Electrical Data on UTS's Encapsulated with Sylgard 184 (First Study) after 420 Days Outdoor Exposure

Exposure Condition	Lexan Cover		No Cover		Tedlar Cover	
	FET Ratio*	Solar Cell Power, % of Original**	FET Ratio*	Solar Cell Power, % of Original**	FET Ratio*	Solar Cell Power, % of Original**
Phoenix, 45°S	0.3	97, 106	0.3	98, 99	8.6	99, 103
Miami, 45°S	0.3	96, 99	0.2	80, 81	0.1	59, 77
EMMA	0.3	88, 91	0.3	92, 93	0.1	95, 98
EMMAQUA	0.3	97, 105	0.2	93, 99	0.1	96, 102

*Ratio of final to original leakage current at 18 volts for a field effect transistor (FET) embedded in the Sylgard 184 pottant.

**From the power point (maximum power) on the IV curve measured by Optical Coating Laboratory, Inc.

TABLE III. Appearance of Encapsulant (Cover) after Accelerated Exposure for 61 Days

Code: C = clear; B = blistered; Bo = bonded to glass; Br = brown; D = dull surface; O = orange; sl. = slight(ly); W = water-white (colorless); Y = yellow

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	-	-	-	-	-	-	-	-
2	C, Y	C, Y	C, Y	C, light Br	D, Y - Br	C, Y, sl. D	C, W	C, W
3	C, faint Y 100% Bo	C, faint Y 100% Bo	C, W, 100% Bo	C, faint Y 100% Bo	C, faint Y 100% Bo	C, faint Y 100% Bo	C, pale Y, 100% Bo	C, Y, 90% Bo
4	C, W	C, W	C, W	C, light Br	C, light br sl. B	C, sl. Br spots	C, W	C, W
5	C, W	C, W	C, W	C, W	C, W	C, W	C, W	C, W
6	C, faint Y, 100% Bo	C, faint Y 100% Bo	C, faint Y 100% Bo	C, faint Y 100% Bo	C, faint Y 100% Bo	C, faint Y 100% Bo	C, pale Y, 100% Bo	C, Y, 95% Bo
7	sl. cloudy, W	Y-Br, with W spots	Br, with W ridges	deep Br, with W spots	part Br part W, B	O-Br, fine ridges	C, Y	sl. cloudy, Y-Br
8	C, faint Y	C, Y	Y, D	Y, sl. cloudy	Y, D	Y, D	C. pale O	C, O
9	C, W 100% Bo	C, W 100% Bo	C, W 100% Bo	C, W 100% Bo	C, W 100% Bo	C, W 100% Bo	C, pale Y, 100% Bo	C, Y, 90% Bo

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE IV. Appearance of Copper Circuitry after Accelerated Exposure for 61 Days

Code: B = bright; B- = bright with some dark specks or stains; D = dull; D/G = dull with gray-green spots

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	D	D	D	D	D/G	D/G	D	most D, some B
2	D	D	D	D	D	D	most B, some D	B
3	B	B	B	B-	B-	B-	B-	B-
4	B	B	B	part B, part D	B-	B-	B	B-
5	B	B	B	B	B	B	D	B
6	B	B	B-	B	B-	B-	B	B-
7	D	D	D	D	part B, part D	D	B	D
8	B	B-	B	B-	B-	B-	B	B
9	B	B-	B-	B-	B-	B-	B	B

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE V. Summary of Effects of Accelerated Exposure for 61 Days

Code: Cu = copper circuitry dull; E = encapsulant brown in color;
G = 2B74 more than 10% debonded from glass cover;
Cell = power reduced more than 10%

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu
2	Cu	Cu	Cu	Cu E	Cu E	Cu		
3								
4				E	E			
5							Cu	
6						G		
7	Cu	Cu E	Cu E	Cu E Cell	E	Cu E		Cu E
8								
9								

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE VI. Appearance of Encapsulant (Cover) after Accelerated Exposure for 61 Days Followed by Steam Exposure for 12 Days

Code: C = clear; B = blistered; Bo = bonded to glass; Br = brown; D = dull surface; M = milky; O = orange; sl. = slight(ly); W = water-white (colorless); Y = yellow

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	-	-	-	-	-	-	-	-
2	C, Y	C, Y	C, Y	C, light Br, striated 5% lost	C, Br	C, Y	C, W	C, W
3	C, W, 5% Bo	sl. cloudy, W, 95% Bo	C, nearly W 0% Bo	C, faint Y, 100% Bo, "worm tracks"	C, faint Y 90% Bo	C, faint Y 5% Bo	C, Y 30% Bo	C, Y 95% Bo
4	pale Y 90% M	Y, 10% M	Y, 20% M	Y, 10% M	C, Y, many cracks, 5% M	off-white, B 100% M	C,W over Cell 3; M,B over Cell 6	10% M (all over Cell 6)
5	C, W, B over Cell 2	C, nearly W, some dirt	C, nearly W	C, W	C, W, some dirt	C, W, sl. B over Cell 2	C, W, B over Cell 5	C, W
6	C, faint Y 20% Bo	C, faint Y, 85% Bo	C, faint Y 20% Bo	C, faint Y 100% Bo	C, faint Y 100% Bo	C, faint Y 95% Bo	C, Y 95% Bo	C, Y, 98% Bo
7	C, Br	tan, greatly B	Br, greatly B	part Br part tan, B	15% C, Br; 85% tan, B, cracked	mostly tan, "furry"	C, Y	60% C, Br; 40% tan, rough
8	sl. cloudy, Y	sl. cloudy, O	sl. cloudy, O	sl. cloudy, O	cloudy, O-Br	cloudy, deep O	cloudy, deep O	sl. cloudy, deep O
9	C, W 80% Bo	C, W 100% Bo	C, W 25% Bo	C, W 95% Bo	C, W 25% Bo	C, W 30% Bo	C, W 40% Bo	C, W 25% Bo

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE VII. Appearance of Copper Circuitry after Accelerated Exposure for 61 Days Followed by Steam Exposure for 12 Days

Code: B = bright; B- = bright with some dark specks or stains; D = dull; D/G = dull with gray-green spots

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	D/G	D/G	D/G	D/G	D/G	D/G	D/G	most D, some B
2	D	D	D	D	D	D	most B, some D	B-
3	B-	B-	B-	B-	B-	part B, part D	B-	B-
4	(not visible)	D	D	D	D	(not visible)	B-	B-
5	B-	B-	B	B-	B	B	D	B
6	B-	B	B-	B	B-	B-	B	B
7	D	(not visible)	(not visible)	(not visible)	(not visible)	(not visible)	D	D
8	B	B-	B	B-	seems B (hard to see)	seems B (hard to see)	seems B (hard to see)	seems B (hard to see)
9	B	B-	B-	B-	B-	B-	B	B-

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE VIII. Summary of Effects of Accelerated Exposure for 61 Days Followed by Steam Exposure for 12 Days

Code: Cu = copper circuitry dull; E = encapsulant brown in color and/or opaque; G = 2B74 more than 10% debonded from glass cover; Cell = power reduced more than 10%

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	Cu Cell**	Cu	Cu	Cu Cell**	Cu Cell**	Cu Cell**	Cu Cell**	Cu
2	Cu Cell**	Cu Cell**	Cu Cell**	Cu E	Cu E Cell**	Cu Cell**	Cell**	Cell**
3	G Cell**		G Cell**	Cell**	Cell**	G Cell**	G Cell**	Cell**
4	Cu? Cell	Cu	Cu	Cu E	Cu E (cracked)	Cu? E Cell	E Cell	Cell
5							Cu	
6	G	G	G				Cell	
7	Cu E Cell	Cu E Cell	Cu E Cell	Cu E Cell	Cu? E Cell	Cu Cell	Cu	Cu E Cell
8								
9	G		G		G	G	G	G

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

**Cells with long circuitry path gave lower power than those with short circuitry path in 17 of 19 cases. See Table IX.

TABLE IX

Effect of Length of Circuitry Path
on Solar Cell Power after Accelerated Exposure
for 61 Days Followed by Steam Exposure for 12 Days

Substrate	Approximate Percent of Original Power	
	Shorter Circuitry Path	Longer Circuitry Path
Ceramic	99	71
	102	80
	69	0
	80	82
	97	0
	100	0
	103	81
	99	78
	83	0
	82	0
	97	0
	98	0
	93	4
	94	67
	87	89
	96	0
	91	0
	91	80
Ceramic	95	0
Enameled Steel	66	74
	51	51
	74	28
	99	86
Enameled Steel	93	4
Epoxy	90	85
	41	42
	36	67
	41	47
	59	28
	50	40
Epoxy	41	76

NOTE: Fraction of pairs of cells in which the longer circuitry path was associated with lower power: ceramic 17/19, steel 3/5, epoxy 3/7.

Table X. Summary of Performance of Encapsulant Systems after Accelerated (Xenon Lamp) Exposure (61 Days) Followed by Steam Exposure (12 Days)

Encaps. System No.*	Solar Cell Power Loss	Corrosion of Copper Circuitry	Degradation of Encapsulant Cover or Pottant	Debonding of Glass Cover
1	Up to 100% power loss after steam exposure, attributed to corrosion of thin Cu plating on circuitry	Dull before steam exposure		
2		Dull before steam exposure	Yellowed by light. Lost integrity by high light + high temp.	
3				Av. 48% debonded after steam
4	Up to 72% loss, attributed to opacity after steam exposure	Dull after steam exposure	Darkened by high light + high temp. Milky after steam exposure	
5				
6	One cell failed (unexplained)			Av. 23% debonded after steam
7	Up to 72% loss, attributed to opacity after steam exposure	Dull before steam exposure	Severely degraded before steam, then further blistered	
8				
9				Av. 48% debonded after steam

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE XI. Ratio of Final to Original Leakage Current at 18 Volts for FET's after Accelerated Exposure for 61 Days Followed by Steam Exposure for 12 Days

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	(open)	(short)	(open)	(open)	(open)	(open)	(open)	17
2	(open)	22	390	(open)	(open)	(open)	(open)	(open)
3	10^6	1.7	0.4	1.1	(open)	10^6	(open)	10^5
4	(open)	(open)	0.9	0.9	1.5	(open)	10^7	2.2
5	720	8.6	13	11	8.7	14	(open)	0.3
6	(open)	1400	10^5	10^4	10^4	10^5	(short)	10^5
7	1.0	12	0.9	0.5	360	27	2	10^6
8	1.7	10^5	1900	5000	10^5	10^4	10^6	10^4
9	700	2400	1300	0.4	305	10^4	10^4	10^4

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE XII. Appearance of Encapsulant (Cover) after Accelerated Exposure for 61 Days Followed by Steam Exposure for 31 Days

Code: C = clear; B = blistered; Bo = bonded to glass; Br = brown; D = dull surface; M = milky; O = orange; sl. = slight(ly); W = water-white (colorless); Y = yellow

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	-	-	-	-	-	-	-	-
2	C, pale Br	C, pale Br	C, pale Br	C, light Br, striated, 10% lost	C, pale Br	C, pale Br	C, W	C, W
3	C, deep Y, 0% Bo	C, deep Y, 5% Bo	C, deep Y, 0% Bo	C, Y 0% Bo	C, Y-Br, 0% Bo	C, deep Y, 0% Bo	C, Y-Br, 5% Bo	sl. cloudy, 95% Bo
4	Y, 100% M	Y, M, except over cell 3	Y, some-what M	white, rough, M except over cell 6	white, rough, M except over cell 3	B, M, lost over cells	C, W, sl. M over part part of cell 6	C, W over cell 3; M over cell 6
5	C, sl. tint, B over cell 2	C, sl. tint	C, sl. tint	C, sl. tint	C, sl. tint	C, v. sl. tint	C, v. sl. tint	C, v. sl. tint
6	C, Y, 10% Bo	C, Y at edges, 5% Bo	C, deep Y, 10% Bo	C, Y, 2% Bo	C, Y at edges, 100% Bo	C, Y at edges, 10% Bo	C, Y, 2% Bo	C, Y 98% Bo
7	cloudy, deep Br, B	tan, B, some lost over cell 6	tan, B, opaque	deep Br, B	tan, rough, opaque	tan, rough, part lost over cells	rough, opaque over part of cells	C, Br, part lost over cell 6
8	red-Br, sl. cloudy	dark red-Br, sl. cloudy	dark red-Br, sl. cloudy	dark red-Br, sl. cloudy	dark Br, nearly opaque	dark Br, nearly opaque	dark red-Br, nearly opaque	dark red-Br, nearly opaque
9	C, Y, 20% Bo	C, deep Y, 10% Bo	C, Y, 2% Bo	C, Y, 5% Bo	C, Br, 5% Bo	C, Br at edges, 20% Bo	C, Br at edges, 20% Bo	Y, cloudy, 60% Bo

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE XIII. Appearance of Copper Circuitry after Accelerated Exposure for 61 Days Followed by Steam Exposure for 31 Days

Code: B = bright; B- = bright with some dark specks or stains; D = dull; D/G = dull with gray-green spots

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	D/G	D/G	D/G	D/G	D/G	D/G	D/G	brown
2	D, dark	D, dark	D, dark	D, dark	D, dark	D, dark	part B, part D and dark	B, with dark spots
3	B, with many dark spots	B, with stains	B-	B, with large dark specks	mostly dark-stained	mostly dark-stained	mostly dark-stained	part B, part stained
4	(not visible)	(not visible)	(not visible)	(not visible)	D	D	D	D
5	B-	B, with dark spots	B	D	B	slightly D	D	slightly D
6	part B, part stained	B, with dark stains	mostly dark stained	B-	B, with dark stains	part B, part stained	mostly B	mostly B
7	(not visible)	D, dark	(not visible)	(not visible)	(not visible)	(not visible)	D	D, dark
8	stained	(not visible)	(not visible)	(not visible)	(not visible)	(not visible)	(not visible)	(not visible)
9	part B, part stained	some B, most dark	B, with stains	B, with much staining	D, dark	most B, some dark	part B, part stained	part B

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE XIV. Summary of Effects of Accelerated Exposure for 61 Days Followed by Steam Exposure for 31 Days

Code: Cu = copper circuitry dull; E = encapsulant brown in color and/or opaque; G = 2B74 more than 10% debonded from glass cover; Cell - power reduced more than 10%.

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	Cu Cell**	Cu Cell**	Cu	Cu	Cu Cell**	Cu Cell**	Cu Cell**	Cu Cell**
2	Cu E Cell**	Cu E Cell**	Cu E Cell**	Cu E Cell**	Cu E Cell**	Cu E Cell**	Cell**	Cell**
3	G Cell**	G Cell**	G Cell**	G Cell**	Cu G Cell**	Cu G Cell**	Cu G Cell**	Cell**
4	Cu? E Cell	Cu E Cell	Cu Cell	Cu E Cell	Cu E Cell	Cu E Cell	Cu Cell	Cu E Cell
5		Cell		Cu		Cu	Cu	Cu
6	G	G	Cu G	G	Cell	G	G Cell	
7	Cu E Cell	Cu E Cell	Cu E Cell	Cu E Cell	Cu? E Cell	Cu E Cell	Cu E Cell	Cu E
8	Cu E Cell	Cu? E Cell	Cu? E Cell	Cu? E Cell	Cu? E Cell	Cu? E	Cu? E Cell	Cu? E Cell
9	G	G	G	G	Cu E, G	G	G Cell	G Cell

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

**Cells with long circuitry path gave lower power than those with short circuitry path in 15 of 16 cases. See Table XV.

TABLE XV

Effect of Length of Circuitry Path
on Solar Cell Power after Accelerated Exposure
for 61 Days Followed by Steam Exposure for 31 Days

Substrate	Approximate Percent of Original Power	
	Shorter Circuitry Path	Longer Circuitry Path
Ceramic	97	72
	93	95
	97	91
	99	0
	44	0
	102	0
	83	0
	96	32
	50	0
	98	0
	82	0
	81	67
	74	0
	83	79
	78	0
Ceramic	93	0
Enameled Steel	64	46
	76	48
	65	65
	10	30
	37	38
	0	86
	100	48
	96	97
	96	52
	96	89
	99	96
	95	90
	84	88
	84	83
	79	82
	85	88
	94	0
	86	95
	83	0
Enameled Steel	93	95

TABLE XV

(Continued)

Substrate	Approximate Percent of Original Power	
	Shorter Circuitry Path	Longer Circuitry Path
Epoxy	45	64
↑	54	54
	30	26
	49	53
	25	18
	99	92
	78	64
	92	94
	86	84
	87	84
	90	92
	80	81
	90	90
	80	80
	88	84
	92	94
	86	91
	88	88
	90	92
	84	86
	89	91
↓	90	82
Epoxy	95	89

NOTE: Fraction of pairs of cells in which the longer circuitry path was associated with lower power (neglecting pairs where readings were the same): ceramic 15/16, steel 10/19, epoxy 9/19.

TABLE XVI. Summary of Performance of Encapsulant Systems after Accelerated (Xenon Lamp) Exposure (61 Days) Followed by Steam Exposure (31 Days)

Encaps. System No.*	Solar Cell Power Loss	Corrosion of Copper Circuitry	Degradation of Encapsulant Cover or Pottant	Debonding of Glass Cover
1	Up to 100% loss after steam exposure, attributed to corrosion of thin Cu plating as well as Mo/Mn circuitry beneath	Dull before steam exposure		
2		Dull before steam exposure	Pale brown. Lost integrity by high light + high temp.	
3		Much dark staining	Deep yellow	Av. 87% debonded after steam
4	Up to 100% loss, attributed to opacity after steam exposure	Dull after steam exposure	Milkiness increased from 12 to 31 days steam exposure	
5	Less than 10% except for once cell	Dull under some conditions		
6	Two cells failed. One lost 17%, other lost <10%.	Much dark staining	Yellow at edges in some cases	Av. 70% debonded after steam
7	Up to 83% loss, attributed to opacity after steam exposure	Dull before steam exposure	Partly lost over cells between 12 and 31 days steam exposure	
8	Up to 21% loss, attributed to darkening	(Circuitry not visible)	Dark red-brown, sometimes nearly opaque	
9	Up to 17% loss	Much dark staining	Brown at edges in some cases	Av. 82% debonded after steam

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE XVII. Effect on Substrates of Accelerated Exposure for 61 Days Followed by Steam Exposure for 31 Days

Substrate	Observed Effects
Ceramic	None
Enameled Steel	Slight rusting at corners and very slight rusting at back edges.*
Epoxy	No warping. Bleaching and fiber bloom (loss of resin at surface) under most severe conditions.

*Immersion of a substrate in 1% NaCl for 32 days resulted in appreciable rusting only at the corners, where enamel coverage was imperfect.

TABLE XVIII. Ratio of Final to Original Leakage Current at 18 Volts for FET's after Accelerated Exposure for 61 Days Followed by Steam Exposure for 31 Days

Encaps. System No.*	Exposure Conditions: UV Intensity, Temp., Rel. Hum.							
	0.66,28, 100	1.00,43, 0	1.00,43, 100	1.00,72, 0	1.00,72, 100	0.66,64, 100	0,72,0	0,72,100
1	(open)	(short)	(open)	(open)	(open)	(open)	(open)	(open)
2	(open)	1300	10^3	(open)	(open)	(open)	(open)	(open)
3	(open)	10^4	7	340	(open)	(open)	(open)	(open)
4	(open)	(short)	10^5	(open)	15	(open)	(short)	11
5	840	(open)	10^5	(open)	26	286	(open)	1.0
6	(short)	(open)	10^5	(short)	10^5	10^5	(short)	10^3
7	10	12	9	5	8	10^3	(short)	10
8	(short)	(short)	(short)	10^4	10^4	10^4	10^4	10^4
9	(short)	10^5	(short)	(short)	10^4	(short)	10^4	10^5

*Encapsulant System No.	Substrate	Pottant/Cover
1	Ceramic	None
2	"	Parylene C
3	"	2B74 (polyurethane) + glass
4	Steel	1B73 (acrylic)
5	"	Sylgard 184
6	"	2B74 + glass
7	Epoxy	Nitrocellulose lacquer
8	"	2B74
9	"	2B74 + glass

TABLE XIX

Absorbance Data for Plastic Films
Exposed in the Solar Furnace

Plastic Film (0.13 mm. Thick)	Calorimeter Reading, cal./cm.^{2}/sec.	Exposure Time, Hours	$\log_{10}(\frac{1}{P})$, where P = Fraction of Original Transmittance at 360 nm.
Lexan 8740 (not UV-stabilized)	7.0	0.20	0.0031
	12	0.083	0.0061
	12	0.33	0.0066
	12	4.0	0.0474
	33	0.33	0.0137
	33	1.0	0.0607*
	33	2.0	0.0921
	33	4.0	0.4583
Polystyrene (clear, biaxially oriented)	7.0	0.20	0.0106
	12	0.083	0.0113
	12	0.33	0.0030
	12	4.0	0.0877
	33	0.33	0.0082
	33	1.0	0.0324
	33	2.0	0.1170
	33	4.0	0.2568

*Measured 3 days after exposure. A measurement at 11 days after exposure gave 0.0645, a 6% increase over the first determination.

TABLE XX

Tensile Test Data for Polystyrene Film
Exposed in the Solar Furnace at 1400 Suns (33 cal./cm.^{2}/sec.)

Exposure Time, hours	Breaking Stress, psi	Fraction of Original Breaking Stress
0 (control)	9,900	
	9,700	
	10,450	
	10,300	
mean:	10,088	1.00
0.33	9,700	
	9,400	
mean:	9,550	0.95
1	8,900	
	6,100	
mean:	7,500	0.74
2	5,100	
	5,100	
mean:	5,100	0.51
4	7,800	
	9,100	
mean:	8,450	0.84

NOTE: To convert to megapascals, multiply values in psi by 0.00689476.

TABLE XXI

Tensile Test Data for Lexan Film

Exposed in the Solar Furnace at 1400 Suns (33 cal./cm.^{2}/sec.)

Exposure time, hrs.	Yield Stress, psi	Breaking Stress, psi	Ultimate Elongation, %	Fraction of Original Breaking Stress
0 (control)	8,400 8,700 8,750 9,100	10,300 8,900 10,100 10,500	116 111 116 115	
means:	8,738	9,950	115	1.00
0.33	8,400 8,300	9,100 9,100	92 85	
means:	8,350	9,100	89	0.91
1	7,750 -	7,600 8,050	80 40	
means:	7,750	7,825	60	0.79
2	- 8,200	6,700 8,000	100 78	
means:	8,200	7,350	89	0.74
4	- -	2,600 2,500	- -	
means:		2,550		0.26

NOTE: To convert to megapascals, multiply values in psi by 0.00689476.